CRISIL Risk and Infrastructure Solutions Limited

in Association with

Indian Institute of Technology Madras

AGENCE FRANÇAISE DE DÉVELOPPEMENT (AFD)

&

INDIAN RENEWABLE ENERGY DEVELOPMENT AGENCY LIMITED (IREDA)

# Study on Tidal & Waves Energy in India: Survey on the Potential & Proposition of a Roadmap

## Final Report

*December 2014*

## Document Version Details

| | |
|---|---|
| **DATE** | December 31, 2014 |
| **VERSION** | 3 |
| **STATUS** | FINAL |
| **CLIENT** | Agence Française De Développement (Afd)<br>& Indian Renewable Energy Development Agency Limited |

## Abbreviations

| Abbreviation | Full Form |
|---|---|
| ADB | Asian Development Bank |
| ADEME | Agence de l"Environnement et de la Maîtrise de l"Énergie |
| AEP | Annual Energy Production |
| AFD | Agence Française De Développement |
| APPC | Average Pooled Power Purchase Cost |
| BBDB | Backward Bent Duct Buoy |
| BIMEP | Biscay Marine Energy Platform |
| BNEF | Bloomberg New Energy Finance |
| BOM | Bureau of Meteorology of Australia |
| CAGR | Compound Annual Growth Rate |
| CAPEX | Capital Expenditure |
| CEA | Central Electricity Authority |
| CERC | Central Electricity Regulatory Commission |
| CFD | Contracts for Difference |
| COMFIT | Community Feed-in-Tariff |
| CRE | Energy Regulation Commission of France |
| CRIS | CRISIL Risk & Infrastructure Solutions Limited |
| CRZ | Coastal Regulation Zone |
| CSIRO | Commonwealth Scientific and Industrial Research Organization |
| DECC | Department of Energy & Climate Change of United Kingdom |
| DEG | Deutsche Investitions- und Entwicklungsgesellschaft |
| DMRPS | Dynamic Minimum Renewable Purchase Standard |
| ECB | External Commercial Borrowing |
| EIA | Environmental Impact Assessment |
| EMP | Environmental Management Plan |
| ETI | Energy Technologies Institute |
| EUR | Euro |
| EXIM | Export Import |
| FEM | France Energies Marines |
| FIT | Feed-in-Tariff |
| GBI | Generation Based Incentives |

| Abbreviation | Full Form |
|---|---|
| GOI | Government Of India |
| GPCL | Gujarat Power Corporation Limited |
| GSFC | Goddard Space Flight Center |
| HAT | Highest Astronomical Tide |
| ICOE | International Conference On Ocean Energy |
| IEX | Indian Energy Exchange |
| IFC | International Finance Cooperation |
| IIT | Indian Institute of Technology |
| INR | Indian Rupee |
| IREDA | Indian Renewable Energy Development Agency Limited |
| IRENA | International Renewable Energy Agency |
| JNNSM | Jawaharlal Nehru National Solar Mission |
| JRC | Joint Research Center |
| LAT | Lowest Astronomical Tide |
| LCOE | Levelised Cost of Energy |
| LIBOR | London Interbank Offered Rate |
| MAT | Minimum Alternate Tax |
| MHHW | Mean Higher High Water |
| MHW | Mean High Water |
| MLLW | Mean Lower Low Water |
| MLW | Mean Low Water |
| MNRE | Ministry of New & Renewable Energy |
| MRCF | Marine Renewables Commercialization Fund |
| MSL | Mean Sea Level |
| MSP | Maritime Spatial Planning |
| MTL | Mean Tide Level |
| NAPCC | National Action Plan on Climate Change |
| NASA | National Aeronautics and Space Administration |
| NBFC | Non-Banking Financial Company |
| NEP | National Electricity Policy |
| NHPC | National Hydro Power Corporation Limited |
| NIO | National Institute Of Oceanography |
| NIOT | National Institute Of Ocean Technology |
| NREL | National Renewable Energy Laboratory |
| OTEC | Ocean Thermal Energy Conversion |

| Abbreviation | Full Form |
|---|---|
| OPEX | Operating Expenditure |
| OWC | Oscillating Water Column |
| PFC | Power Finance Corporation |
| PLF | Plant Load Factor |
| PLOCAN | Oceanic Platform of the Canary Islands |
| PPA | Power Purchase Agreement |
| PTO | Power Take-Off Systems |
| PXIL | Power Exchange of India Limited |
| QREN | Quadro de Referência Estratégica Nacional |
| QUICKSCAT | Quick Scatter-o-meter |
| REC | Renewable Energy Certificate |
| REFIT | Renewable Feed-In-Tariff |
| REIF | Renewable Energy Investment Fund |
| ROC | Renewable Obligations Certificate |
| RPO | Renewable Purchase Obligation |
| RPS | Renewable Purchase Standard |
| SEA | Strategic Environment Assessment |
| SEAI | Sustainable Energy Authority Ireland |
| SERC | State Electricity Regulatory Commission |
| SPV | Special Purpose Vehicle |
| TRL | Technology Readiness Levels |
| TSB | Tidal Stream Barrage |
| TST | Tidal Stream Turbine |
| UKERC | UK Energy Research Center |
| USA | United States of America |
| USD | United States Dollar |
| VGF | Viability Gap Funding |
| WAM | Wind-Wave Model |
| WBREDA | West Bengal Renewable Energy Development Agency |
| WEC | Wave Energy Convertor |

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# 1. Executive Summary

Renewable energy is considered to be an important driver for low carbon growth and India‟s sustainable solution to issues related to electrification in remote locations. India has around 150 GW of known renewable energy potential. This potential is likely to be even greater than 150 GW, if all the sources including tidal, wave, geothermal with significant generation capacity will be mapped. Even with such a vast potential, only ~22% of renewable energy potential (i.e. 33 GW[1]) is developed in the country.

The total installed capacity in India is around 256[2] GW (*as on October 2014*) primarily dominated by thermal sources of energy. Thermal energy (*comprising of oil, coal and natural gas*) contributes around 69%[3] of total installed capacity followed by hydro, renewables and nuclear energy. Renewable energy forms ~12.8%[4] of total installed capacity. This also shows that we are progressively moving towards the National Action Plan for Climate Change (NAPCC) target of renewable energy (i.e. 15% by 2020).

India‟s commitment to reduce carbon emissions and fuel related concerns in conventional sector has increased in recent years; the Government has shifted focus towards development of renewable energy sources. This step will help India in achieving energy security, reducing adverse environmental impact, lowering carbon intensity and realizing its aspirations for leadership in high-technology industries by contributing to a more balanced regional and global development.

**Figure 1: Installed capacity in India as on October 2014**


However, in order to achieve the NAPCC targets as specified above, India needs a substantial increase in renewable energy capacity in the next five years. The targets specified in the 12th plan period aim at faster, sustainable and more inclusive growth as is also evident from ambitious targets indicated in working group report of Ministry of New and Renewable Energy (MNRE).

Even with potential for providing predictable and sustainable electricity generation with relatively lower visual impact; ocean power / geothermal constitutes a meager percentage of the 30 GW in the 12th

[1] *Source : CEA*
[2] *Source : CEA*
[3] *Source : CEA*
[4] *Source : CEA and MNRE*

plan renewable energy targets for grid-connected renewable capacity addition. It has been learnt that marine power has traditionally suffered from relatively high cost and limited availability of sites with sufficient potential, thus constricting its total availability. However, following recent technological developments and improvements, both in design & turbine technology; it is expected that it will result in lowering of levelised costs for harnessing marine energy to competitive levels.

CRISIL Risk & Infrastructure Solutions Limited in association with Indian Institute of Technology, Madras hereafter referred to as ("CRIS-IITM") has been commissioned by Agence Francaise Developpement (AFD) and Indian Renewable Energy Development Agency Limited (IREDA) to carry out a project titled "*Study/ Survey & Preparation of Road Map on Tidal Energy Projects in India*". This project is being conducted as part of Memorandum of Understanding (*MoU*) between IREDA and MNRE, Government of India. The project involves carrying out a study on tidal & wave energy in India and survey on the potential & proposition of a roadmap.

## 1.1 Findings

### 1.1.1 Technical/Economical Potential Analysis

Wave and Tidal are two different ways to extract energy from movement of water in the sea and oceans.

Wave energy exists due to the movement of water near the surface of the sea. Waves are formed by winds blowing over the sea surface, and the water acts as a carrier for the energy. The amount of energy in waves depends on their height and period (the time between successive peaks). **The annual average power per unit length of wave crest (e.g. 20-40 kW/m) is the primary indicator of how energetic a particular site is.**

Tidal streams are caused by the rise and fall of the tides, which occur twice a day around the coast. As water flows in and out of estuaries, it carries energy. The extractable energy depends on the speed of the flowing stream and the area intercepted. This is similar to wind power extraction, but because water is much denser than air, an equivalent amount of power can be extracted over smaller areas and at slower velocities. **The mean spring peak velocity is the primary indicator of how energetic a tidal stream site is.**

The most promising and predictable form of marine renewable energy is the tidal power. It is non-polluting, reliable and predictable. Even with its potential for predictable and sustainable electricity generation with low visual impact, tidal power still accounts for only a fraction of a percent of the world‟s total electricity generation. However the trend is gradually improving, with numerous tidal power plants being constructed or planned along coastlines around the world. Internationally, there is an established trend of tidal barrages being very successful. However, stream turbines have not achieved similar level of success due to their complexity.

#### Status of development of tidal and wave energy technologies worldwide

Currently, the United Kingdom (UK) and United States of America (USA) are the most active countries in developing wave and tidal conversion technologies followed by Norway and Canada. Demand for wave generation is expected to grow in the next decade. Wave energy is still one of the least mature renewable energy technologies; however since the global potential of wave energy is significantly higher than tidal energy, we expect significant development in the future given adequate political support.

Wave technology shows no design consensus so far and the bulk of wave projects are still in testing phase or pre-commercial phase. Primary, secondary and tertiary conversions are three methodologies with which wave energy can be harnessed. Absorbers, Attenuator, overtopping devices, oscillating water column, oscillating wave surge convertor, buoyant moored device and hinged contour device are technologies using the abovementioned methodologies to harnessing wave energy.

Tidal energy attention has been growing in the recent years, but currently most of the projects are still in the early stages. Within tidal, current and barrage are the two main approaches. Tidal barrage is the most successful technology so far in marine energy. It has been employed in most of the operational projects around the World. On the other side, tidal stream/current seems to be most developed technology (*based on number of projects and suppliers*). With a thrust to develop a least cost option, tidal stream/current technology has reached early stages of maturity. Less installation time-frame is one of the benefits being offered by tidal stream/current technology. Some early research has also been conducted in other techniques including tidal lagoon and tidal fence.

Most of the new technologies in tidal and wave are still under testing or pre-commercial phase. However, few of them have achieved commercial scale-production including axial flow turbine (*tidal stream technology*), cross flow turbine (*tidal stream technology*) and point absorber (*wave energy technology*). The readiness level for new technologies in tidal & wave energy is summarized in the table below.

**Table 1: Readiness level for new technologies in tidal & wave energy**

| Technology Type | Technology Resource Deployment Status | | | Readiness Level |
|---|---|---|---|---|
| | | | | |
| Attenuator | - | 29 projects | - | Open water system testing & demonstration and operation |
| Axial Flow Turbine | 64 projects | 1 project | - | **Commercial-scale production/application** |
| Closed-cycle | - | - | 3 projects | System integration and technology laboratory demonstration |
| Cross Flow Turbine | 28 projects | 2 projects | - | System integration and technology laboratory demonstration |
| Hybrid | 1 project | - | - | **Commercial-scale production/application** |
| Oscillating Water Column | - | 14 projects | - | Open water system testing & demonstration and operation |
| Oscillating Wave Surge Converter | 2 projects | 30 projects | - | Open water system testing & demonstration and operation |
| OTEC - Closed Cycle | - | 1 project | - | System integration and technology laboratory demonstration |
| Overtopping Device | - | 3 project | - | Open water system testing & demonstration and operation |
| Point Absorber | - | 19 projects | - | **Commercial-scale production/application** |

| Technology | Technology Resource Deployment Status | | | Readiness Level |
|---|---|---|---|---|
| Reciprocating Device | - | 2 projects | - | System integration and technology laboratory demonstration |

*Source: CRIS analysis & http://en.openei.org*

There are about four tidal power plants in operation with capacity varying from 1 MW to 254 MW. As per the study, all four have utilized tidal barrage technology to harness tidal energy. The details of major plants are given in the table below.

**Table 2: Details of Operational Tidal Power Plants**

| Name | Country | Technology | Capacity (MW) |
|---|---|---|---|
| Shiwa Lake Tidal plant | South Korea | Tidal Barrage | 254 |
| La Rance Tidal power plant | France | Tidal Barrage | 240 |
| Annapolis Royal tidal plant | Canada | Tidal Barrage | 20 |
| The Jiangxia Tidal power station | China | Tidal Barrage | 3.2 |
| The Kislaya Guba Tidal facility | Russia | Tidal Barrage | 0.4 |

*Source: CRIS Analysis*

The 240 MW La Rance Tidal Barrage in France was commissioned in 1966 and is the oldest plant under operation. The plant consists of 24 bulb type turbine generators 5.35 metres in diameter, 470 tonnes in weight, and rated at 10 MW each which generate electricity whether the tide is going in or out (developed by Électricité de France). This peak of 240 MW of power is sufficient to power 4% of the homes in Brittany - equivalent to the consumption of a town the size of Rennes. The average power generated is 68 MW for an annual output of around 600 million kWh units of electricity, at a capacity factor of around 26%.

The Sihwa Lake Tidal power plant in South Korea is the largest tidal power plant and was commissioned in 2011. The name plate capacity of turbines utilized is similar in both the plants. The basic difference lies in the efficiency of turbines and calculation of capacity.

*Wave and Tidal energy conversion devices are still early stage technologies. Various prototypes have been rolled out to test improvements in turbines and technologies to harness energy from water movement. Tidal being the most predictable form of renewable energy has seen limited exploitation on commercial principles. Within wave energy, the industry is yet to arrive on the consensus on technology/design, as bulk of wave projects are still in testing or pre-commercial phase.*

## Potential of Tidal & Wave Energy in India

**Earlier assessment – Wave & Tidal**

The Ministry of New and Renewable energy (MNRE) made an assessment of the potential of tidal energy in the country. The study indicated an estimated potential of about 8000 MW with 7000 MW in the Gulf of Kambhat, 1200 MW in the Gulf of Kutch in Gujarat, and about 100 MW in the Gangetic delta in Sunderbans in West Bengal. Since, the potential assessment depends largely on the technology and methodology to be used, these figures could be updated continuously based on the proposed technology and methodology.

One of the earliest works reported on the distribution of wave power potential along the Indian coast is credited to Narasimha Rao and Sundar (1982). They employed data gathered from the National Institute of Oceanography (NIO). The data was collected from ships and Indian daily weather reports covering the period 1968 to 1973. Based on their assessment, the wave power potential in India was approximately estimated at 40,000 MW. Even harvesting 10 to 20% of this energy would be a great achievement considering the persisting energy demand.

**Current Assessment – Tidal Energy**

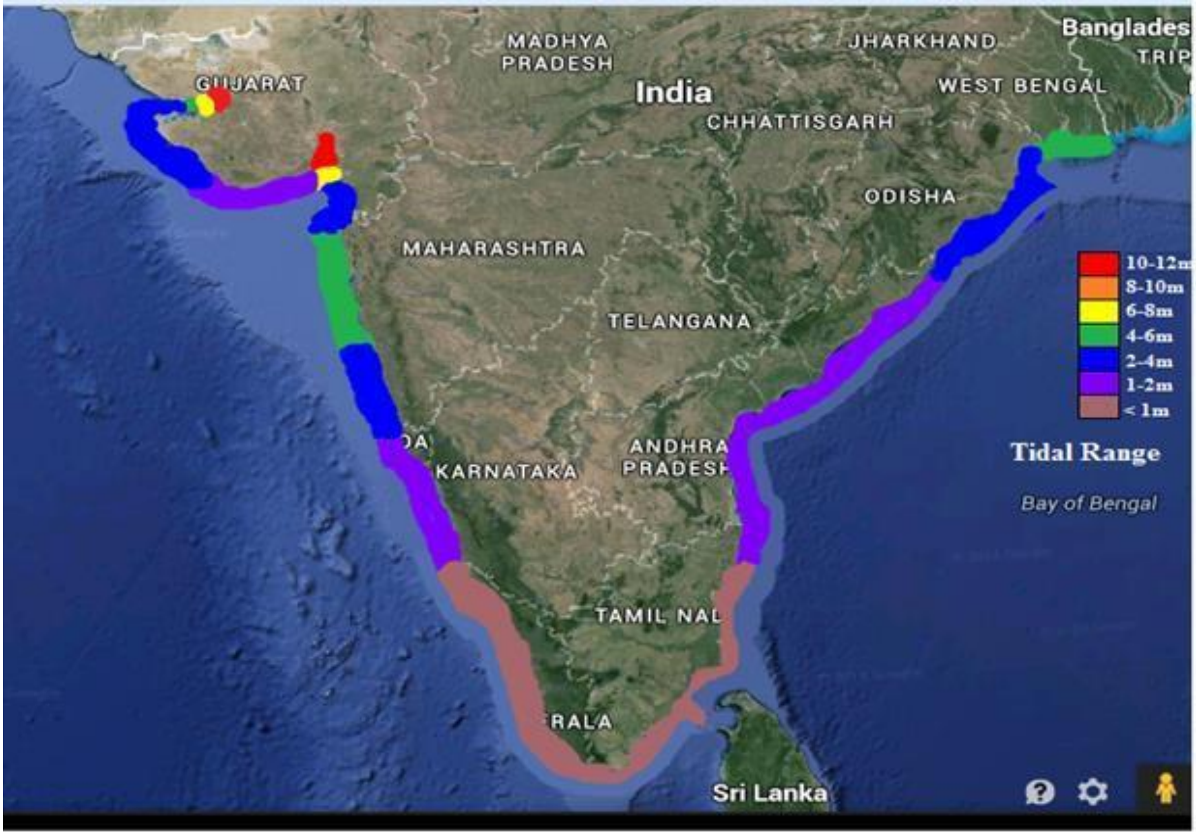
The tides contain both potential and kinetic energy. Potential energy is the energy stored or available when water is available at an elevation higher than normal. This is possible during flooding tides and energy will be available during the ebbing phase. The energy available from a barrage depends on the area of the water surface impounded by the barrage and the corresponding magnitude of the tidal range. The tidal generators connected with stream turbines (*immersed in sea*) make use of the kinetic energy of the water stream which in turn spins the turbine and drives the generator to produce electricity.

As discussed in earlier paragraph; within tidal, current and barrage are the two main approaches to harness the kinetic and potential energy of the tide respectively. Tidal barrage technology can be deployed to harness the potential energy of tides; whereas tidal stream turbine technology can be utilized to harness the available kinetic energy of tides. Tidal stream turbine technology has reached early stages of maturity and is being deployed on commercial scale in the world. Presently, several versions of turbines are available in the market which could be deployed based on the site characteristics including tidal current velocity, water depth etc. Hence, the potential of tidal energy has been re-assessed after taking into account the recent technological developments and improvements.

The previous assessment of tidal potential has been reviewed using the scientific data available from the relevant sources. The source for making estimation includes national hydro-graphic charts, Wx tide, NIO and simulations carried out by IIT-Madras. The tidal level at various locations along the Indian coastline has been identified using the NIO tide table and by performing a harmonic analysis. The tidal magnitudes, spring tide and neap tide range has been estimated using 37 species for 46 locations along the coastline. These tidal levels were validated by deploying sea level gauges at several stations along the Indian coast.

Tidal currents were estimated using hydro-dynamics modeling. The order of tidal currents has a strong correlation with the tidal range; as the maximum tidal current is usually observed in locations of higher tidal range. The coastline of India is further classified into several classes separately for the tidal range (*in meters*) and tidal current (*in meter/second*) to identify the potential locations. The spring tidal range along Indian coast is depicted in the figure 2. Taking into account the tidal range and tidal current at identified locations, theoretical assessment of potential energy and kinetic energy has been carried out.

**Figure 2: Spring tidal range along Indian coast (Source: IIT-Madras)**



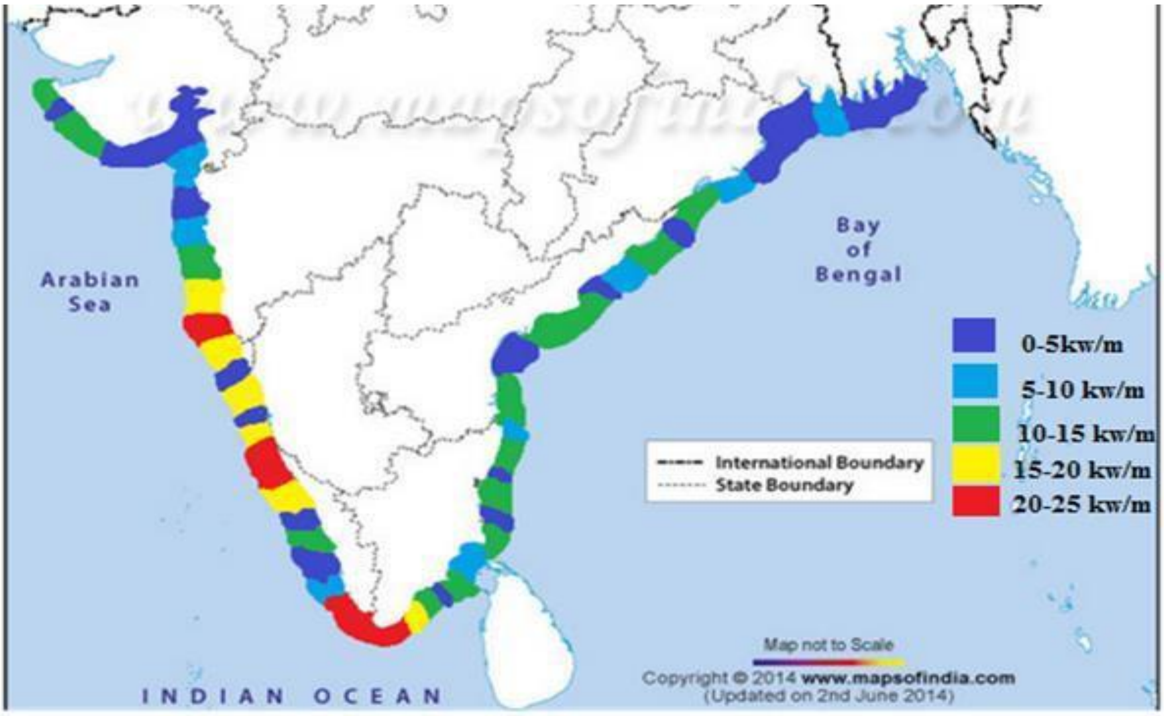

As can be understood from the above figure, there are only three regions in India with largest concentration of tidal energies namely Khambat, Kutch and Sudarbans regions. As could be observed from the figure, the western coastline of India has higher tidal range. It has been learnt, when flow velocities are enhanced at the openings on the coastline, it is possible to realize reasonably good amount of energy in terms of kinetic energy. For regions with low tidal range, the obvious choice will be to modify the flow pattern of the tidal flooding and ebbing so that reasonably good currents are generated.

In view of recent technological advancements to harness tidal energy at the identified locations; achievable tidal potential is estimated at around 12,455 MW. In the present assessment, the deployment of tidal stream turbine technology is envisaged at identified locations of Khambat and Kutch regions. Besides, some other potential sites are also identified with large backwaters, where barrage technology could be used.

**Current Assessment – Wave Energy**

In order to explore the wave energy potential along Indian coast in detail, 10-year simulation wave data has been utilized. The third-generation wind-wave model WAM has been employed to generate wave data of ten years from 1993 to 2002 in the Indian Ocean [*IIT-Madras, 2007*]. The hindcast wind of QUICKSCAT with a resolution of $0.25^{o}$ x $0.25^{o}$ has been utilized. The offshore wave climate off the Indian coasts has been extracted at salient points. The distributions of wave power potential along the Indian coastline are projected in the figure 3. A gridded wave simulation has been carried out over entire Indian Ocean for 5 years using WIND-WAVE model on 80 locations. The data has been further validated using numerical simulation at many buoy locations.

**Figure 3: Distribution of wave energy along the coastline (Source: IIT-Madras)**




From the map mentioned in figure 3, it can be observed that the contour 10-15 kW/m is distributed almost evenly along the western and eastern coasts. Further, the wave contours of 15-20 kW/m are observed along the west coast, off viz., Maharashtra, Goa, Karnataka and Kerala. The presence of higher power along the west coast could probably be due to the strong waves during the south-west monsoon. Maximum wave power can be obtained at the southern tip of the Indian peninsula (*Kanyakumari, Nagercoil district, Koodankulam*) due to the effect of refraction and the presence of strong winds prevailing in the region. The wave technology can be combined with the off-shore wind technology to harness maximum renewable energy potential at above identified sites.

Based on the length of coastline (*km*) and contour power level (*kW/m*), power flux crossing the contour has been estimated for entire coastline. Based on the revised estimations of wave power contour and power flux crossing the contour along different maritime states, the potential is assessed at 50 GW. However, considering wave power above 10 KW/m, total wave power potential is assessed at 41 GW. It is to be noted that entire 41 GW may not be harvested due to natural constraints and site conditions such as water depth. Therefore, the realistic estimate at each site need to be made based on detailed surveys along a particular coastal stretch.

**Figure 4 : Comparison of current and earlier assessment**


*Source: IIT-Madras & CRIS analysis*

*~53 GW of ocean energy potential exists in India with a capacity utilization factor in the range of 15-20% for wave energy and 25%-30% for tidal energy. Most of the extractable potential exists on the western coastline of India. It includes the State of Gujarat, Maharashtra, Kerala, Karnataka, UT of Goa and Southern peninsula. Combination of off-shore wind with marine technologies helps in harnessing maximum renewable energy potential.*

## Potential locations for harnessing tidal and wave energy

Based on the above research, potential locations are depicted in the figure below for harnessing tidal and wave energy. As discussed in earlier paragraphs, the critical parameters for assessing the site for harnessing tidal energy depends on tidal range, tidal current velocity, water depth, and reservoir availability. Similarly, availability of wave power, land, erosion proneness, and local demand of power are some of the criterion for selection of site & technology for harnessing wave energy.

**It should be noted these sites are identified based on the assessment of parameters defined above. A realistic estimate of each site can be made based on detailed site surveys and feasibility study along a particular coastal stretch.** The estimation of capacities that may be installed in coastal states along with potential locations is also shown in the map below. The details and exact coordinates of these sites are provided in the chapter 4 of the report. We have identified potential sites for harnessing tidal potential in state of Gujarat, West Bengal and Tamil Nadu. Besides, large backwaters are available on the coastline where tidal barrage could be developed for harnessing the tidal energy.

**Figure 5 : Potential locations for harnessing tidal and wave energy**

**Tidal Energy >12455 MW**

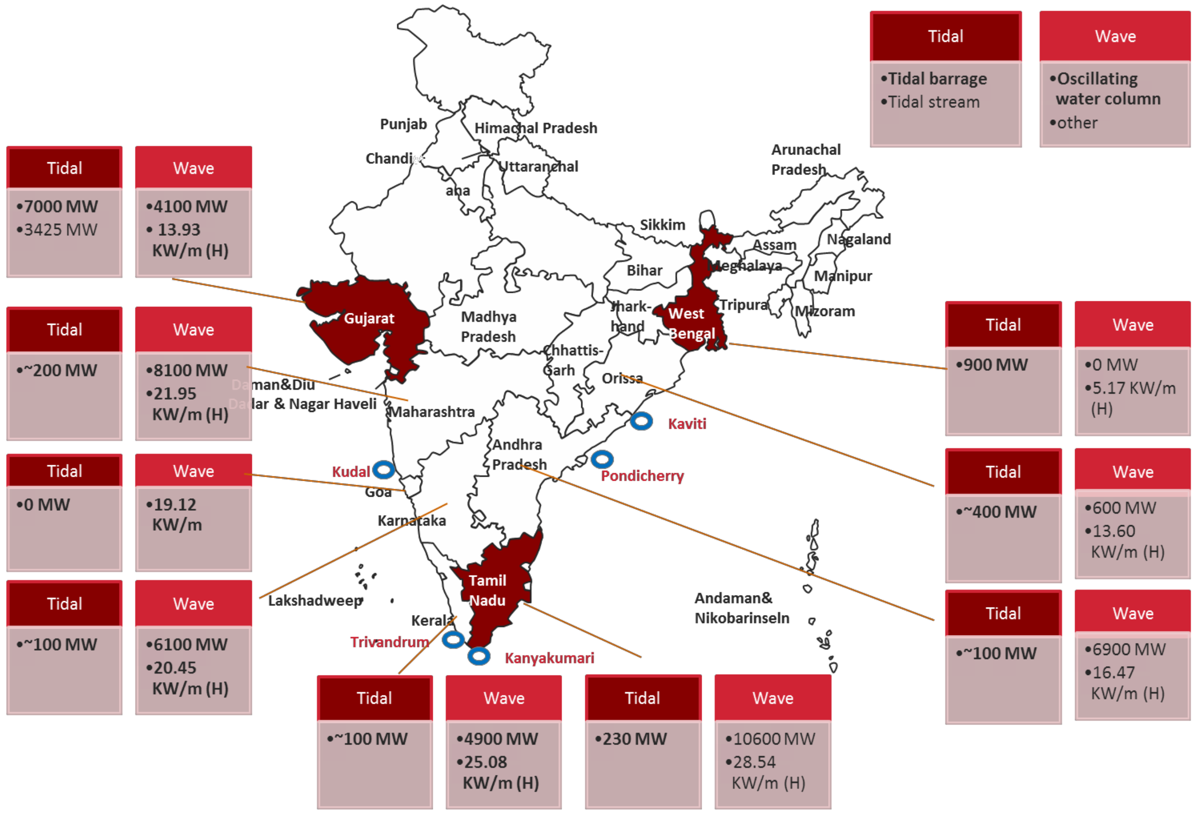
- Potential locations (11555 MW):
  - Gulf of khambat (7000 MW with Tidal barrage technology) & (1425 MW with Tidal stream technology)
  - Gulf of Kutch (2000 MW with Tidal stream technology)
  - Palk Bay-Mannar Channel (230 MW with tidal barrage technology)
  - Hoogly river, South of Haldia, Sunderbans (900 MW with tidal barrage technology)
- Other locations (900 MW):
  - South Gujarat / North Maharashtra / Orissa with class-II-tidal range and stream
  - Karnataka/Maharashtra/Kerala/Andhra with class-III-tidal range and stream

**Wave Energy > 41000 MW**

- Identified locations (>2000 MW over the stretch of 10 Kms):
  - Kudal, Maharashtra (21.95 KW/m) with OWC technology
  - Trivandrum, Kerala (25.08 KW/m) with OWC technology
  - Kanyakumari, Tamil Nadu (23.39 KW/m) with hybrid wind and wave energy
  - Puducherry, Tamil Nadu (10.59 KW/m) with offshore breakwater plus OWC
  - Kaviti, Andhra Pradesh (14.96 KW/m) with over topping device
- Other potential locations (>10 GW):
  - Along the west coast of India including Maharashtra, Goa, Karnataka, Kerala.
  - Locations on the Southern tip of India including Kanyakumari, Nageroil district and koondankulam have highest wave power

*Source: IIT-Madras & CRIS analysis*

**Figure 6: State wise potential and sites for harnessing tidal and wave energy in India**




*Source: IIT-Madras & CRIS analysis*

## List of stakeholders involved in development of technology at central and state level

Various stakeholders are involved in the development of the marine technology at the central and state levels. The exhaustive list is mentioned below.

- **Research & Information Institutes** like Indian Institute of Technology-Madras, National Institute of Ocean Technology, National Institute of Oceanography, Indian National Center for Ocean Information Services, Indian Ocean Global Ocean Observing System, Susi Global Research Center, Naval Physical & Oceanographic Laboratory, National Center for Earth Science Studies;
- **Educational Institutes/Universities** like IIT–Madras, Kunjali Marakkar School of Marine Engineering, Cochin University of Science & Technology, Department of Meteorology and Oceanography, Andhra University, Department of Ocean Engineering & Naval Architecture, IIT Kharagpur.
- **Private sector developers** involved in the development of ocean energy such as DCNS energy, Alstom India, EDF France and Atlantis, UK.
- **Others** government, public and private agencies involved includes Ministry of New & Renewable Energy, Ministry of Earth Sciences, Indian Renewable Energy Development Agency Limited, AFD-France, and CRISIL.

### 1.1.2 Environment Assessment

#### Enabling framework exists in the countries leader in marine technologies

There are number of countries who are actively working in the field of marine energy for development of wave and tidal energy projects. The following table provides a snapshot of international regulatory and policy environment for tidal and wave energy projects.

**Table 3: Summary of enabling framework in countries leader in marine technologies**

| Country | Tidal Energy Targets | Revenue Options | Open Sea Testing Centre | Loans, Subsidies & Guarantees | R & D and Demonstration Funding |
|---|---|---|---|---|---|
| **UK** | Specified under the RE Roadmap | No Feed-in-Tariff (FIT) ; Covered under ROC Scheme | Yes | Yes | Yes |
| **France** | Specified under the European Directive | FIT available ($Cent 22 / unit); Covered under Renewable Energy Certificate (REC) Scheme | Yes | Yes | Yes |
| **Canada** | Specified under Marine RE Technology Roadmap | FIT available ($Cent 56 /unit) | Yes | Yes | Yes |
| **South Korea** | Defined under RE plan | No FIT; Covered under RPS Scheme | No | Yes | Yes |
| **Ireland** | Defined under National RE Action Plan | FIT available ($Cent 56 /unit) | Yes | Yes | Yes |
| **China** | 2030 Strategic roadmap under development | FIT available | Under development | Yes | Yes |
| **Denmark** | No | FIT available ($Cent 10 /unit) | Yes | Yes | Yes |
| **USA** | No | No FIT; Covered under Clean Energy bonds | Yes | No | Yes |

*Source: SI Ocean*

Most of the above mentioned countries including China, Ireland, South Korea, Canada, France and UK have specified specific tidal energy targets in their roadmaps. These countries have been using FIT or REC route coupled with loans, grants and subsidies to make tidal and wave projects financially feasible. In Indian context, FITs have been the most successful option for renewable energy projects coupled with various additional tax incentives. A similar support could be adopted for development of marine energy based technologies/projects too. Besides, removal of policy & market barriers is also critical for deployment and commercialization of wave & tidal energy in India.

It is to be noted that despite the efforts being made by various national governments, the tidal and wave energy sector faces some critical issues, which needs to be resolved for promoting marine energy resources. Some of the key barriers in the development of tidal and wave energy projects are outlined below.

- Technological barriers
- Environmental barriers
- Financing barriers

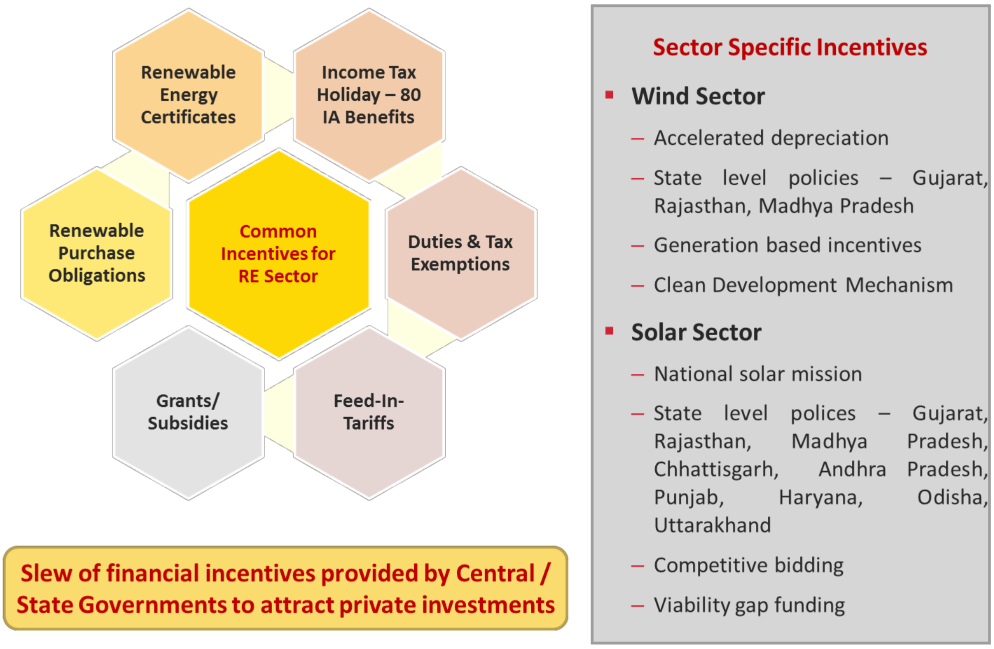
Currently, most of the tidal and wave energy projects are being funded through a combination of government grants/subsidies and project developer investments. Most of the countries are providing funds for research, development and project demonstration activities. Further, incentives in the form of FIT, RECs, and tax incentives are also being provided in selected countries.

However, lack of operational experience and project bankability issues make these projects more risky for financers as compared to other renewable energy projects. Hence, there is a need to promote awareness related to existing and upcoming technologies in marine energy generation. Further, the governments need to develop various possible frameworks for promoting marine energy.

## Status of enabling environment for development of renewable energy in India

The Government of India has introduced various supportive policy and regulatory initiatives to promote development of renewable energy sector. The key incentives presently being offered by the central and state-level governments to attract private sector investments in renewable sources are depicted below.

**Figure 7: Incentives offered in India in renewable energy**




It has been observed that these promotional incentives have attracted private sector participation in the renewable sector in the last decade. It is evident from the fact that renewable capacity[5] has grown

[5] *Source : Published data in annual reports of MNRE, CEA*

from 3.5 GW in FY 02 to 31.7 GW in FY 14. Wind energy has been the fastest growing renewable sources in the last decade. In terms of installed capacity, wind energy stands at 21,996 MW, followed by small hydro (3,856 MW), solar (2,765 MW), bagasse (2,689 MW), biomass (1,365 MW), and waste to energy (106 MW).

## Financing Options

Most of the financing sources offer debt at the rate of 12-13% per annum typically for 8-10 years; Similarly, the cost of equity offered by most of the equity investors (*without government guarantees*) have higher return expectations within a short period. It has been learnt from the past developments, renewable energy project based on any new technology being cost intensive projects could not attract the investors on its own. Therefore, high cost and limited availability of debt is a major problem being faced by developers. In case of foreign currency loans, benefit of low interest rates is negated by high hedging costs. Equity is currently available for attractive renewable energy projects; future availability is linked to debt availability in medium to long term. However, revenue model selection needs to be based on risk reward profile, commercials / charges and ground situation / feasibility in each state.

*Robust policy framework provided at Central Level has been key enabler for Grid connected power. However, over last couple of years; delays in regulatory clarity have led to lag in renewable energy capacity addition. State(s) level incentives are a critical enabler, but are limited due to financial health constraints of the utilities.*

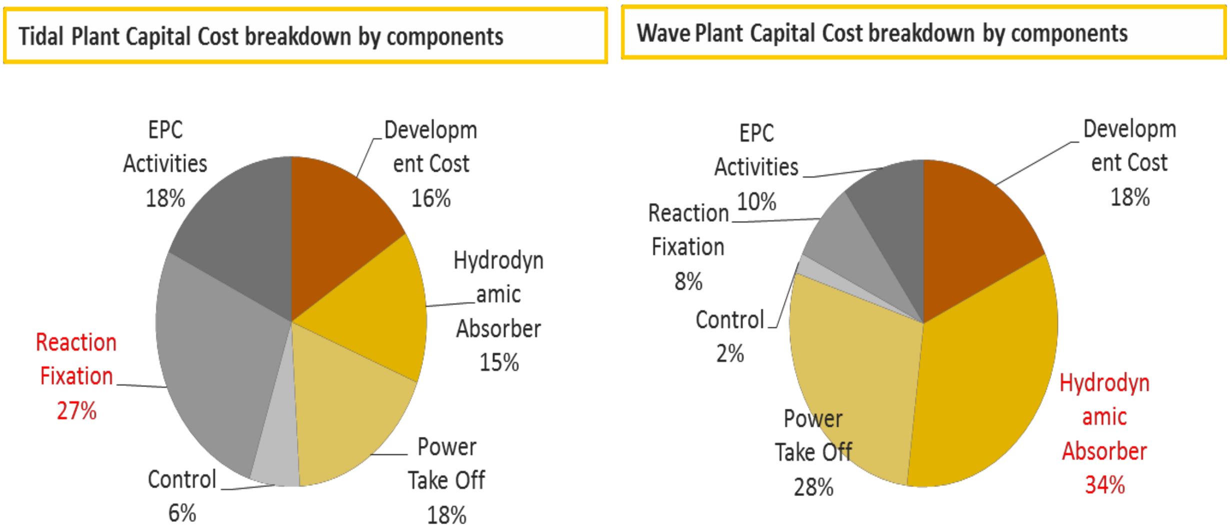
## Commercial aspects of Tidal and Wave Energy

Marine is amongst the most capital intensive forms of renewable energy. Partly due to its pre-commercial stage of development, the LCOE for marine energy project is difficult to estimate. The best estimates show that it has the highest LCOE due to:

- Absence of scale of economies;
- Lower efficiency rates (from fine-tuning);
- Lack of meaningful debt financing;

Currently, there is an excess of financial capital in the market but it is quite risk averse. Out of the USD 30 billion invested in the form of project finance for clean energy assets around the world in last quarter solar and wind account for the bulk of the investment and “Marine” is a rounding error. The capital expenditures (capital costs) for tidal and wave energy development begin long before construction starts. Contrary to the case for other technologies, the LCOE of both wave and tidal technologies have been trending upward in response to new data points. The estimates of fixed O&M costs was found almost doubled in the quarterly reports of 2012 submitted by the UK Carbon Trust‟s Marine Energy Accelerator (MEA). This development has raised the estimated LCOE by 9-10%.

**Figure 8: Tidal and wave capex breakdown**



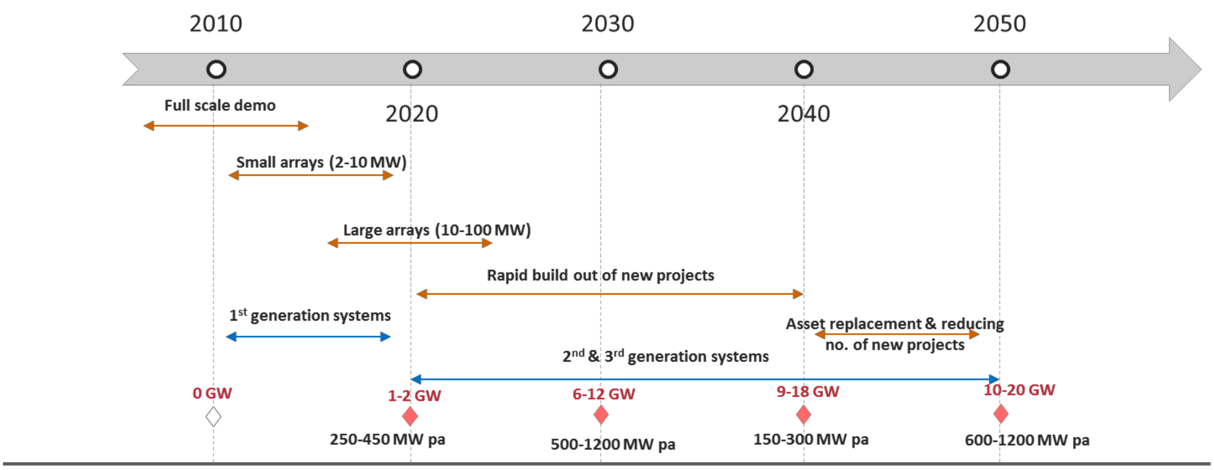

*Source: NREL, Cost and Performance of Renewable Energy, 2012*

The early array costs for wave energy are higher than for tidal but in the long term wave energy has larger overall resource potential, so therefore could deliver at similar LCOE to the long term tidal estimates.

It has been understood that the estimated cost of energy from first arrays is relatively high compared to other renewables at a more advanced stage of development (*such as offshore wind*) but rapid reduction in costs from prototypes is already evident and there is reason to expect that significant reduction in cost of energy will continue as deployment increases.

The figure mentioned below depicts the credible paths to reduce capital and operating costs and to increase yield. With the experience from the deployment of small arrays (2-10 MW) of tidal power projects, the market is expected to start moving towards a mature phase of project development. The developers, financiers and power off taking agencies will start adapting the learnings from past projects. Due to these learning‟s, the risk and perception of risk will fluctuate to lower levels, which eventually may have a significant impact on the cost estimates of development of projects.

**Figure 9: LCOE Projection[6] (UK Tidal Deployment and Cost Scenario)**




| | | | | |
|---|---|---|---|---|
| CAPEX | $5.88-11 m/ MW | $3.14-5.5 m/ MW | $3.14-4.0 m/ MW | $1.5-2.0 m/ MW |
| OPEX | $c 2.5-6.3 / kW | $c 1.6-3.9 / kW | $c 0.8-2.5 / kW | $c 0.47-1.6 / kW |
| CF | 25-35% | 35-40% | 37-42% | 40-45% |
| Efficiency | 75-85% | 90% | 90-95% | 95-98% |
| LCOE | $c 25-60/ kWh | $c 14-28/kWh | $c 11-16 / kWh | $c 8.0-13 / kWh |

*Source: UK Energy Research Centre Marine Energy Technology Roadmap*

Wave and tidal energy is currently seen as high risk because of a lack of operational experience and this has a significant impact in terms of higher hurdle rate requirements. There is a need to build up reliability and operation experience to increase certainty in LCOE estimates and reduce risk for investors.

In 2011, the Government of Gujarat entered into an MoU with Atlantis Resources (Gujarat Tidal) Pte limited (*Joint venture of GPCL, Atlantis & PMES*) for carrying out further studies and for implementing a 50 MW Pilot Tidal based power project at Gulf of Kutch at Mandvi. Government of Gujarat has sanctioned INR 700 million (*USD 11.5 million*) as financial assistance for the project. The LCOE worked out at US$ 0.20/kWh or INR 13/kWh. The project has got stalled due to less clarity on financing arrangements.

## Possible Incentives for Promotion of Tidal and Wave Energy

RE incentives available in India needs to be tailored to marine energy needs. The table below showcases the possible incentives available for marine energy development. One of the options to attract investments is to invite private sector participation on pre-approved sites. The initial gap funding from the government could be in form of convertible loans, if the project do not get commissioned within the specified period.

[6] *Please note the cost of financing is considered at par from 2010 to 2050*

**Table 4: Possible incentives for promotion of Tidal and Wave Energy**

| Incentives for RE Sector | Suitability for Wave & Tidal Projects | Remarks |
|---|---|---|
| **Supportive policy, regulatory & institutional structure** | Yes | ▪ Develop a national policy identifying time bound targets (Short, medium & long term), nodal agency, single window clearance & available incentives for pilot as well as commercial projects. |
| **Accelerated Depreciation** | Yes | ▪ Should be available for small scale projects |
| **Renewable Energy Certificates** | No | ▪ REC mechanism has not been successful for established RE technologies (wind & solar). Hence, it should not be implemented for tidal & wave energy projects in the initial phases |
| **Feed in tariffs** | Yes | ▪ Phase wise project specific FIT needs to implemented; higher FIT in initial phase and subsequent lowering of FIT<br>□ Phase 1 : FIT for small scale testing / pilot projects<br>□ Phase 2: FIT for commercial project based on experience from pilot projects |
| **Concessional CD and zero ED, IT Holiday** | Yes | ▪ These benefits would aid in lowering overall cost of power |
| **Low cost financing** | Yes | ▪ Low cost and long tenure funding options would be helpful in lowering the LCOE. |
| **Grants & Subsidies** | Yes | ▪ Government support in terms of grants / subsidies will promote R&D as well as demonstration projects. |

Reduction in the pre-development time is critical for development of marine energy project. Historically, the project with extended lag time i.e. delays in obtaining clearances & approvals resulted in cancellation of project due to cost and time-over run. Therefore, it is a pre-requisite for tidal & wave energy based projects, to have a single window clearances system. This will simplify approval & clearance process from various stakeholders – Department of Fisheries, State Maritime Board, State Transmission Company, Indian Coast Guard, Department of Environment and Forest, Coastal Regulation Zone etc. A list of concerned Ministries and Departments for obtaining clearances is given at Annexure – 1.

### 1.1.3 Importance of harnessing Tidal and Wave Energy in Indian Context

The potential for economic growth, energy security, job creation, and global export inherent in wave and tidal energy technologies is considerable. India has a long coastline with estuaries and gulfs where tides are strong enough to move turbines for electrical power generation. The identified theoretical potential of tidal power is 12 GW and that of wave power is 41 GW. Some of the benefits of harnessing this un-tapped potential are depicted in the figure below.

**Figure 10: Benefits of Tidal and Wave Energy**

**Predictable**
- Produce energy at different known time periods and more consistently than other RE sources
- Will add to overall stability of networks

**Less Visual/noice impact**
- Tidal turbines are located beneath the ocean surface and cannot be seen or heard
- Reduction in carbon emission

**Protection of shores**
- Helps in protection of banks & reduce the risk of floods
- Attract lots of tourist & promote trade through development of harbours, and easy transportation

**Higher energy density**
- Water is ~800 times denser than air
- For a given electricity output, tidal turbines can be much smaller than wind turbines

**Off-grid electricity generation**
- Best source in coastal areas for off-grid electricity generation
- Improvement in standard of living at coastal areas

**Improvement in Socio-Economic Factors**
- Creation of jobs/small scale allied industries
- Helps in development of marine industry in India

## 1.2 Recommendations

### 1.2.1 Strategic Objectives

**Table 5: Strategic Goals**

| Milestone | Priorities | Goals |
|---|---|---|
| **2015** | ▪ Regulatory and policy framework for private sector participation in the development of tidal and wave energy in India | ▪ Define target capacity addition by 2020-30 and design feed-in-tariff and other fiscal and tax incentives for the development of the sector |

| Milestone | Priorities | Goals |
|---|---|---|
| | ▪ Build Task Force comprising of scientists, policy makers, developers and financiers from interested stakeholders and provide public funding for research and development in the sector. | ▪ Collaborate, coordinate, and leverage tidal and wave energy research<br>▪ Sign agreements with the private sector to develop the first 10 pilot arrays |
| **By 2020** | ▪ Demonstration and testing of first 10 pilot arrays<br>▪ Technology innovation | ▪ Financial close on up to 10 pilot arrays<br>▪ Technology innovation to reduce costs, increase reliability, increase yields |
| **By 2030** | ▪ Innovation<br>▪ Supply chain engagement<br>▪ Acceleration of cost reduction standardization and scale-up | ▪ Commercial array installations (30 MW+) |

*Source: CRIS Analysis*

### 1.2.2 Strategic Action Plan

**Table 6: Strategic action plan**

| Year | Research | Market Development | Regulatory System Development |
|---|---|---|---|
| **2015-16** | ▪ Establish a „Task Force"/Forum for taking R&D activities in tidal and wave energy<br>▪ Study environmental effects of tidal and wave power<br>▪ Facilitate access to onshore and offshore testing facilities, devise testing standards, and prioritize testing of components, materials, and subcomponents, as well as full-scale devices | ▪ FIT, capital support and other market incentives for tidal and wave energy<br>▪ Begin work on small demonstration sites and marine electricity integration studies | ▪ Marine energy legislation - dedicated national level policy needs to be prepared to focus on marine energy development.<br>▪ Establish strategic environmental assessment programmes<br>▪ Streamline and accelerate consenting processes by removing excessive administrative and cost burdens |
| **2020** | ▪ On-going technical and environmental research | ▪ Deployment of 10 tidal and device arrays using a stage approach at commercial site<br>▪ Testing and demonstration of wave arrays | ▪ Integrate wave and tidal energy into short- and long-term grid planning |
| **Post 2020** | Commercially competitive tidal barrage and in-stream technology | | |

*Source: CRIS Analysis*

# 2. Background

## 2.1 Objective

India has 150 GW of known renewable energy potential, of which only about 14% has been developed. As per the Government‟s plans, renewable energy is considered to be an important part of India‟s sustainable solution to issues related to electrification. The country‟s renewable energy potential is likely to be even greater than 150 GW, as sources with significant generation capacity have not been mapped yet. Hence, development of renewable energy sources can help India achieve energy security, reduce adverse environmental impact, lower carbon intensity and realize the country‟s aspirations for leadership in high-technology industries by contributing to a more balanced regional and global development.

The National Action Plan on Climate Change (NAPCC) recommended increasing the share of renewable energy to 10% by 2015 and 15% by 2020. In order to achieve these goals, India needs significant capacity increase in the next decade. Further, capacity addition targets for the 12$^{th}$ Plan period aim at faster, sustainable and more inclusive growth as is evident from the ambitious targets indicated in MNRE‟s working group report.

The capacity addition targets for tidal/geothermal constitute a meager percentage out of 30 GW in the 12$^{th}$ Plan targets for grid-connected renewable capacity addition. However, recent technological developments and improvements, both in design and turbine technology, may result in lowering of economic and environmental costs to competitive levels. The main objective of the tidal energy programme being executed by MNRE is to study, test and assess the potential of tidal energy in the country for harnessing power generation.

Marine power has traditionally suffered from relatively high costs and limited availability of sites with sufficient potential, thus constricting its development. In the past, some studies have been conducted to capture the potential of marine energy in India. MNRE has sanctioned a project for setting up a 3.75 MW demonstration tidal power plant at Durgaduani Creek in Sunderbans, West Bengal, to West Bengal Renewable Energy Development Agency (WBREDA), Kolkata. The Government of Gujarat also formed a special purpose vehicle (SPV) with public-private partnership and sponsored a study for large-scale exploitation of tidal energy across the coastline of Gujarat. Although tidal and wave energy technologies are in nascent stages of development as compared to their counterparts, India with its long coastline offers rich possibilities for development of marine energy projects.

Hence, the primary objectives of this assignment are to:

- Update quantification of the potential tidal and waves energy capacity in India,
- Review the ongoing projects and initiatives in this sector, and
- Analyze the adequacy of the existing regulatory framework and business environment for the development of such a technology.

## 2.2 Scope of Work

The detailed scope of work to be covered under this project is as follows:

**Technical / Economical Potential Analysis**

- Describe status of development of the different tidal and waves energy technologies worldwide.

- Analyze and update the existing studies on tidal and waves energy potential in India, based on kinetic and potential energy assessment, taking into account recent technological developments and improvements.
- Identify the potential, lack of data, review the calculations and complete the assessments already done using scientific data available.
- Identify potential locations for harnessing tidal and waves energy based on the above research.
- Give a clear estimation of the capacity that may be installed in India for all the coastal states, per technology with cost estimation per MWh per technology in the Indian context taking seasonal variation into account;
- List the stakeholders involved in the development of this technology at the Central and at the state levels, along with universities, research centers and the private sector, and describe their main activities and organization related to tidal energy.

### Environment Assessment

- Describe the existing regulatory framework, support policies and financial mechanisms in countries which are leaders in the implementation of these technologies.
- Describe the existing regulatory framework that would apply to tidal and waves energy including (but not limited to): generation license, environmental and social clearances, grid connection, and power purchase agreement.
- Describe the existing support policies for the development of tidal and waves energy (if any): tariffs, grant schemes, capacity building.
- List the sources of financing (especially equity and loans) available for renewable energies in India along with their conditions. Compare those costs and conditions with the revenues expected from a tidal and waves energy project.
- Identify the potential barriers that tidal and waves energy projects may face and issue recommendations to overcome them.
- Select between the various policies of GoI or state governments in favor of the development of renewable energies, the schemes which have proven to be more efficient and which would be adapted to tidal and waves energy.

### Roadmap Development

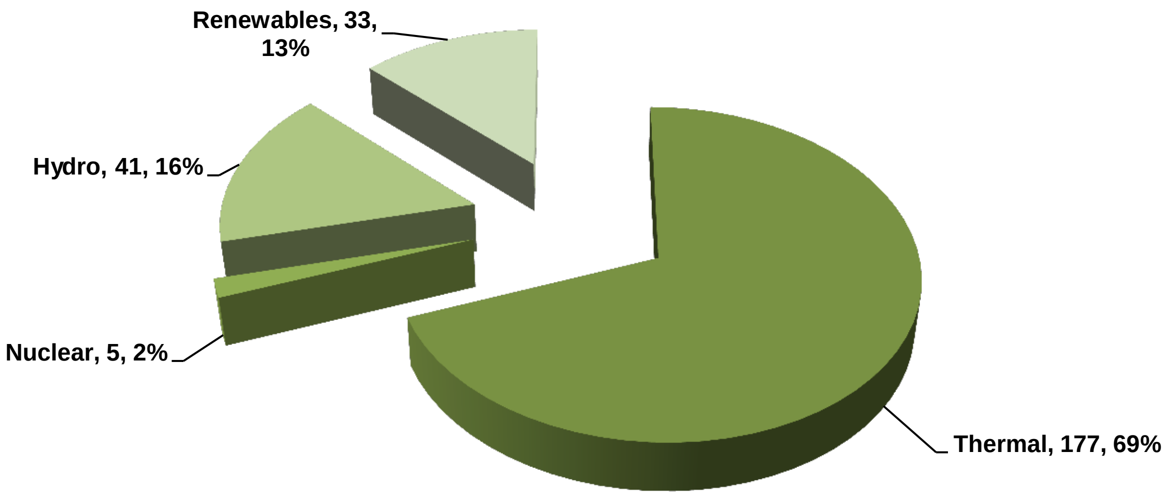
- Present the importance of harnessing tidal and waves energy in the Indian context.
- Present the regulatory amendments required to enable tidal and waves energy projects to come up.
- Propose an adapted institutional set-up to promote these technologies.
- Offer recommendations regarding the financial tools to be provided.
- Propose a realistic objective of installed capacity using tidal and waves energy technologies for 2020 and milestones to be set to achieve such an objective.
- The main conclusions of this report will be presented to IREDA and MNRE‟s managers and the technical team during a one or two-day workshop to be organized by the consultant. It will be complementary to the information already released during the workshop organized by AFD on technology updates, at the beginning of the assignment.

# 3. Introduction

## 3.1 Power Sector in India

India is one of the fastest-developing countries in the world. The country has developed a diversified portfolio of power generation comprising of thermal, hydro, nuclear and renewable sources. The total installed power capacity in India is around 256 GW[7] and is dominated by thermal sources (comprising oil, coal and natural gas) which contribute around 69% (177 GW) to the total installed capacity followed by hydro 16% (41 GW), renewables 13% (33 GW) and nuclear sources 2% (5 GW). The figure below exhibits the latest generation mix from various sources in the country.

**Figure 11: Total installed power capacity in India (GW, %)**




*Source: Central Electricity Authority (CEA) & Ministry of New & Renewable Energy (MNRE) until October 2014*

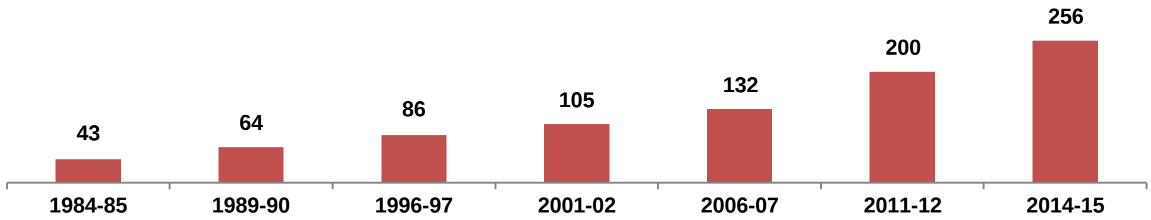
Low-cost thermal generation sources have become the backbone of the Indian power sector due to fuel availability and technological advancements during the last decade. However, in the recent years, with India‟s commitment to reduce carbon emissions and fuel-related concerns in the conventional power sector, the Government has shifted its focus to the development of renewable energy sources.

The Indian power sector has witnessed a compounded annual growth rate (CAGR) of 8.5% in installed capacity during the last eight years, increasing from 132 GW in 2007-08 to 256 GW as on October 2014.

There has also been a sharp rise in the demand for power due to economic growth, demographic changes and lifestyle improvements. Hence, overall situation of power sector in the country is improving due to various Government interventions and private sector participations. The following figure showcases the trend of generation capacity addition over the years in India.

[7] As per Central Electricity Authority (CEA) & Ministry of New & Renewable Energy (MNRE) until October 2014

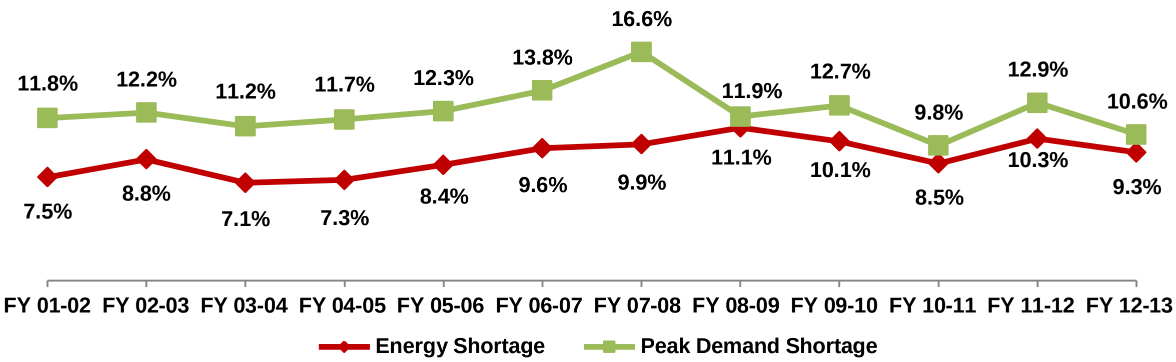
**Figure 12: Installed Capacity Addition in India (GW)**




*Source: Central Electricity Authority (CEA) & Ministry of New & Renewable Energy (MNRE) until October 2014*

However, the continuous growth in installed capacity has not been able to catch up with the rising demand for electricity. As per the Central Electricity Authority (CEA), energy and peak demand shortage remained around 9% and 12.3%[8] respectively on an average basis over the last 12 years; and the trend is expected to continue in the near future. The graph below exhibits the movement of energy and peak demand shortages in the country.

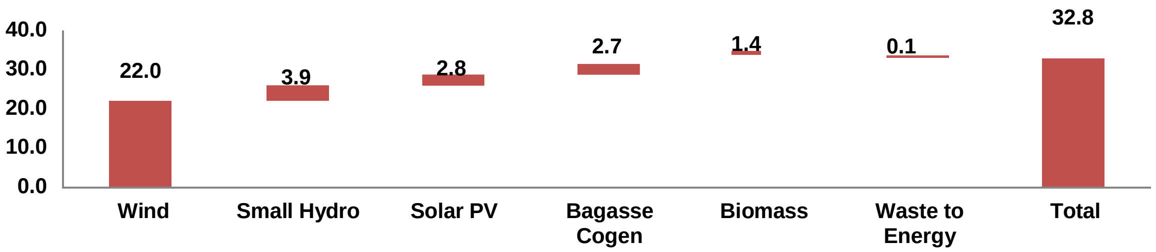
**Figure 13: Trend of Energy and Peak Demand Deficit**




*Source: CEA*

The 12th Five-Year Plan (2012-13 to 2016-17) aims to add 30 GW of renewable capacity that will take the total tally of renewable energy based power plants to about 55 GW in 2016-17. Currently, the total renewable installed capacity stands at more than 32 GW; a source-wise breakup has been provided in the figure below.

**Figure 14: Technology-Wise Share in Installed Renewable Capacity (GW)**



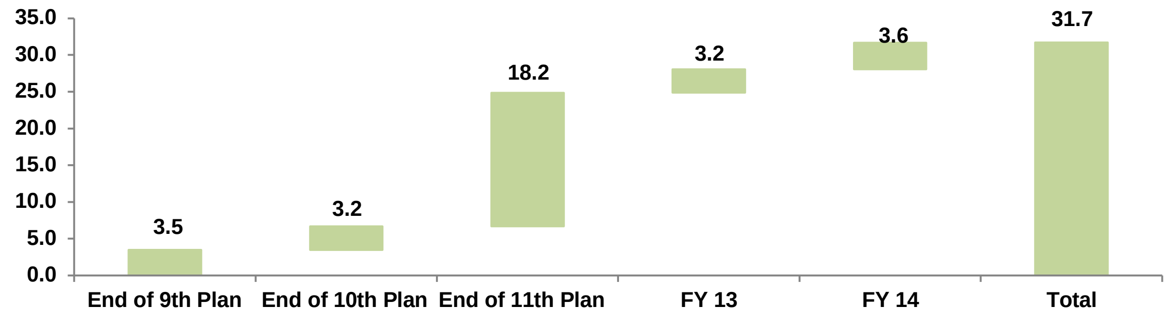

*Source: MNRE*

[8] Central Electricity Authority (CEA) – Annual Report 2010-11 and Load Generation Balance Report FY 11-12 & FY 12-13

As seen from the table above, wind energy has been the major contributor to total renewable capacity addition with over 22 GW (67%) followed by small hydro (12%), solar (8%), bagasse (8%), biomass (4%) and waste-to-energy (0.3%) of renewable installations throughout the country.

So far, the country has performed reasonably well in developing its renewable portfolio, over-achieving renewable capacity addition targets in each five-year plan. Installed capacity has grown from 3.5 GW in FY 02 to ~33 GW in FY 15 with a CAGR of nearly 22% per annum as shown in the graph below.

**Figure 15: Trend of Renewable Capacity Addition (GW)**



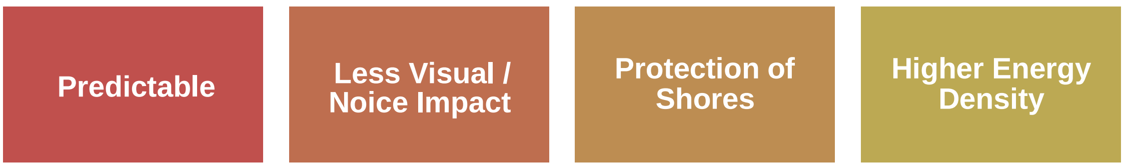

*Source: MNRE*

This has been possible due to the availability of various support programs / initiatives / schemes at the Central and state Government level. Achieving the remaining capacity addition target, which is equivalent to about the present installed capacity, within the next four years, will require a long-term and supportive investment environment.

## 3.2 Importance of harnessing Tidal and Wave Energy in Indian Context

India has a long coastline with estuaries and gulfs where tides are strong enough to move turbines for electrical power generation. Being a green technology, the potential for economic growth, energy security, job creation, and global export is inherited in wave and tidal energy technologies. The identified theoretical potential of tidal power and wave power is 12 GW and 40 GW respectively. The following figure highlights key benefits of harnessing this un-tapped potential, followed by detailed description of each of the highlighted benefits.

**Figure 16: Benefits of tidal and wave energy in Indian Context**



Source: CRIS Analysis

▪ **Predictable**

Since, tidal energy is generated due to the effect of gravitational pull of sun and moon on earth, it is considered as a renewable energy source. As tides follow monthly cycle, which are more predictable in nature, the dependence of tidal energy on rise and fall of tides makes tidal energy a more uniform, reliable and predictable energy source. Similarly, wave energy is reliable because of perpetual motion of ocean waves.

In contrast to tidal and wave energy, other forms of renewable energy such as wind and solar energy are dependent on random weather patterns. Power generated from renewable sources such as wind and solar poses grid integration challenges due to their unpredictable nature. Lack of proper resource prediction tools may result in sudden surge in system frequency resulting in grid stability issues. Hence, grid integration of tidal and wave energy would not poses major grid stability issues.

▪ **Sea Shore Protection**

Offshore breakwaters are used along beaches for providing protection against erosion or to create artificial beaches. Such structures act as a coast protection measure by stabilizing a section of the coast to limit sand erosion. These structures can be combined with tidal and wave energy projects to reap the dual benefits of sea shore protection and harnessing tidal / wave energy. The following figure showcases how the wave energy turbines can be integrated with breakwater to generate electricity.

**Figure 17: Sea shore protection**


Top View

Side View

*Source: SDK Wave Turbine*

▪ **Higher Energy Density**

Water has 830 times" higher energy density than air i.e. it can store a larger amount of energy per unit volume as compared to other forms of renewable energy, such as the wind. Hence, for a given electricity output, tidal turbines can be much smaller than equivalent wind turbines. Further, it is possible to harness energy at low speeds from wave and tidal sources as compared to wind which require comparatively higher speeds.

▪ **Less Visual / Noise Impact**

Tidal and wave power systems have less prominent visual impact as compared to wind and solar systems. They require less space as compared to wind turbine or solar arrays. Since, the wave / tidal turbine equipment is located offshore, either on the surface or below the surface, it doesn't block views or interfere with aviation or radar systems. Furthermore, they produce low / no noise, unlike wind turbines, which produce aerodynamic noise, thereby avoiding disturbance to the marine surroundings.

- **Socio-economic Impacts**

Tidal and wave energy projects provide a number of socio-economic benefits for the local coastal and island population (*where diesel power generation is predominant*) ranging from local electricity production and consumption, aid in navigation, yachting, flood control, bank protection & recovery, etc. Further, construction and operations of wave energy plants could bring significant positive economic impacts to coastal states in the form of local jobs creation, creation of industrial clusters, taxes and duties etc. For example, the La Rance tidal plant has provided a short route for crossing of vehicles thereby decreasing time as well as fuel consumption.

## 3.3 Ocean Energy

Two main types of Energy are commonly known to be harnessed from Ocean: thermal energy transferred through the heat generated by the sun and the mechanical energy from the tides and waves. The former is referred to as OTEC (Ocean Thermal Energy Conversion). Out of the total earth‟s surface 70% is covered by Oceans. Hence, ocean is the largest collector of solar energy. Temperature gradient created by sun‟s heat warms the surface much more than the deeper water. This thermal energy available in the ocean can be used for electricity generation.

There are three types of electricity conversion systems under OTEC: closed-cycle, open-cycle, and hybrid. Closed-cycle system uses a low-boiling point liquid, such as ammonia that can be vaporized by the ocean's warm surface water. The low boiling point liquid is termed as working fluid. The expansion of vapor takes place which in turn drives the turbine. The turbine then drives a generator to produce electricity. In open-cycle system sea water itself is boiled by operating at low pressures. The steam thus produced passes through a turbine/generator. The combination of closed-cycle and open-cycle is the hybrid system.

Ocean mechanical energy is largely different from OTEC. These are forms of energy that are present in motion of ocean water. Tides are driven primarily by the gravitational pull of the moon, whereas, the waves are driven primarily by the wind. As a result, tides and waves are intermittent sources of energy, whereas, ocean thermal energy is fairly a constant, although its gradient, which is more important, varies with location.

Conventionally, a barrage (dam) is used to convert tidal energy into electricity by allowing the water to pass through turbines, and thus activating a generator. Alternatively, tide induced currents are the major under water currents that could be utilized to drive the tidal turbines in a way similar to the wind turbine driven by the wind. The wave energy can be harnessed in three basic ways

i) Overtopping system: It use the wave to fill the reservoir at a level higher than surrounding ocean. The potential energy thus available in the reservoir is captured by the low head turbines;

ii) Moored buoy: It uses the rise and fall of the swells to drive the hydraulic pumps and generate electricity by induced EMF theory;

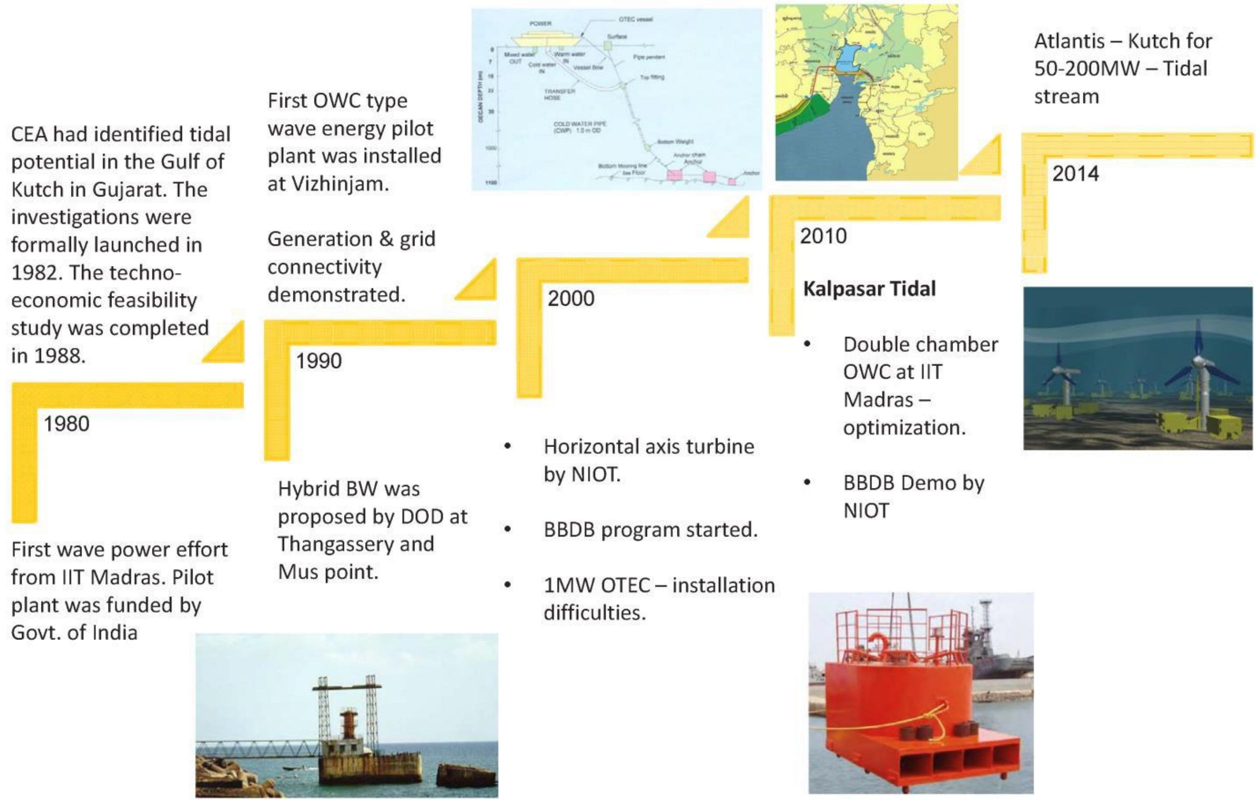
iii) Oscillating water column: It uses the waves to compress air within a container which drives the turbine to generate electricity.

Hence, marine renewables are looked at as an obvious choice for meeting the objective of reducing fossil fuels usage. Given the extent of coastline available[9] with India, there appears to be an

[9] *Indian coastline is over 7000 Kms*

unexplored area of marine renewables. Though India has been able to make some initiatives towards wave energy during the last part of 1980s, their effort has not continued since then. The Vizhinjam study remains a pilot study without significant breakthroughs in terms of structural optimization and power take off (PTO) arrangements. The efforts in India over the past few decades are captured in Fig.1.2 comprehensively. The figure shows that there has not been a focused research and development in this area in India. It also shows the lack of top down planning in India in terms of development of marine renewable technologies. On the other hand, there have been developments elsewhere in the world where very successful pilot studies have been conducted for harnessing tidal energy. The subsequent sections of this chapter and the following chapters try to re-examine the tidal and wave options. This is done with the view of new knowledge gained in other parts of the world and also in India in terms of technology advancement and improved knowledge on the coastal waters of India. The Department of Ocean Engineering, IIT Madras being the original investigators of the Vizhinjam plant is in the right position with their extensive contributions to the coastal zone development and management, including disaster mitigation.

**Figure 18: Historical efforts in India on Marine Renewables**




*Source: IIT Madras and CRIS*

## 3.3.1 Environmental Impacts

A variety of ocean energy technologies and devices are being developed worldwide, and many such devices have been tried through pilot projects. In addition to the technological developments, their environmental effects after implementation and during functioning are of paramount importance.

The lack of deployment experience in wave energy technologies has made it difficult to assess their environmental impacts due to their site specific nature. However, the following issues thoroughly investigated before project implementation. Thus, pilot projects, of region specific nature, are of important in order to assess the possible impacts of each type of technology.

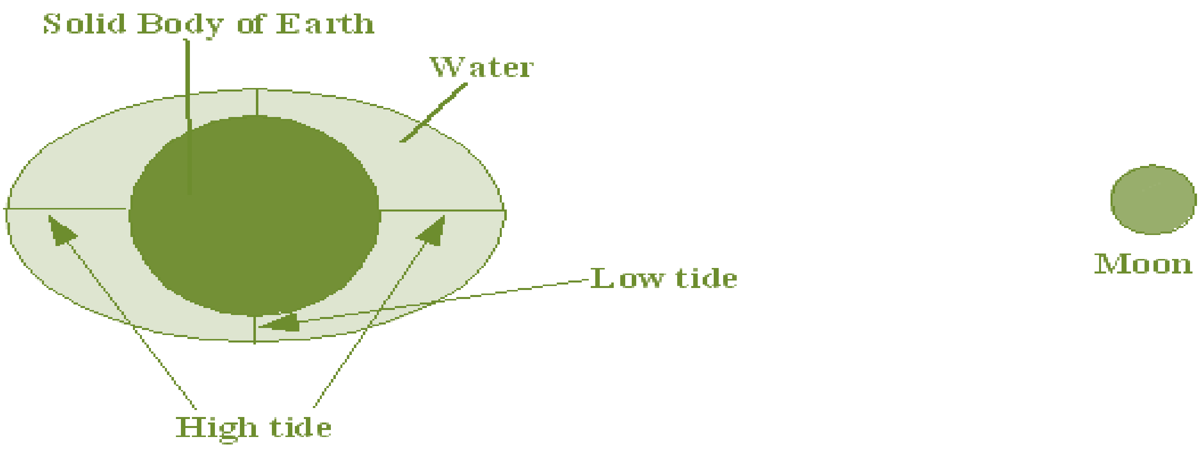
- Coastal processes, sediment transport and contamination.
- Marine water quality assessment.
- Impact on Flora and Fauna.
- Impact on Fish including recreational and commercial fisheries.
- Marine mammals.
- Coastal birds.
- Navigation and marine transport assessment.
- Seascape and visual assessment.
- Marine and terrestrial archaeology and historic seascape assessment.
- Marine and terrestrial noise assessment.

## 3.4 Tidal Energy

Tidal energy is one of the oldest forms of energy harnessed by humans from the naturally occurring phenomena of rise and fall of the ocean‟s water level due to gravitational attraction between the sun, moon and the earth.

A two-way pull from the earth exists between the earth and moon. The moon‟s pull on earth causes the ocean water facing the moon to be pulled towards it, producing the high tide. A similar high tide on the other side of the earth facing away from the moon occurs because the solid part of Earth is being pulled away by the moon as shown in the figure below. The two bulges are the high tides, the area between the bulges are the low tides. Each tidal location is approximately 6.25 hours apart.

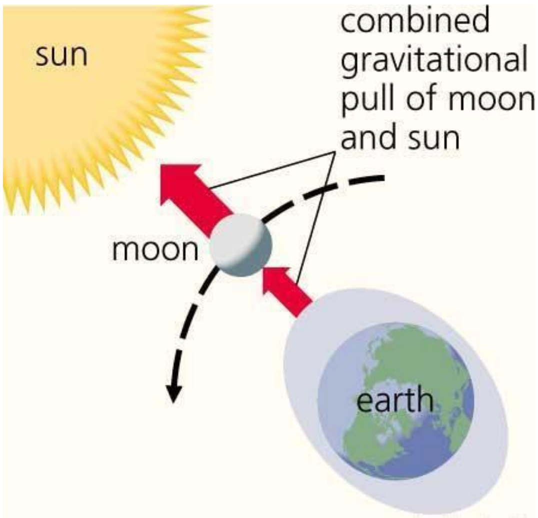
**Figure 19: High Tide & Low Tide**




*Source: Science journals*

Similarly, twice each month, when the sun, moon, and earth are collinear as shown in the following figure, the pulling forces add up to produce the highest and lowest of tides, called spring tides.

**Figure 20: Spring Tide**

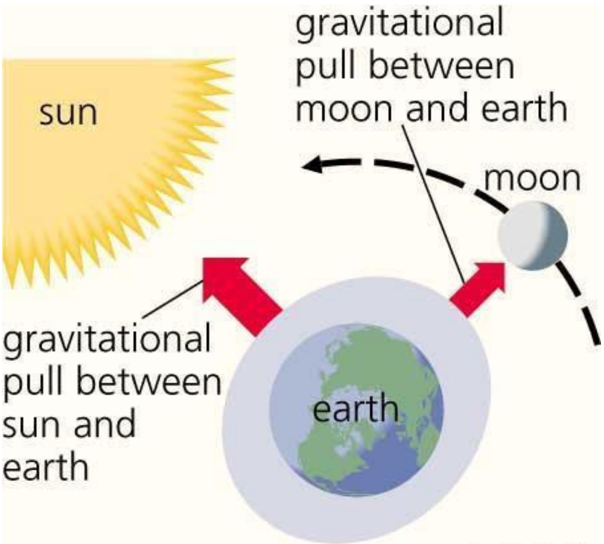



*Source: Science journals*

When the pull of the moon and the pull of the sun on earth are at right angles as shown in Figure 2.3, between the new moon and the full moon, the tides are not as high or low as at other times of the month. These weaker tides are called neap tides.

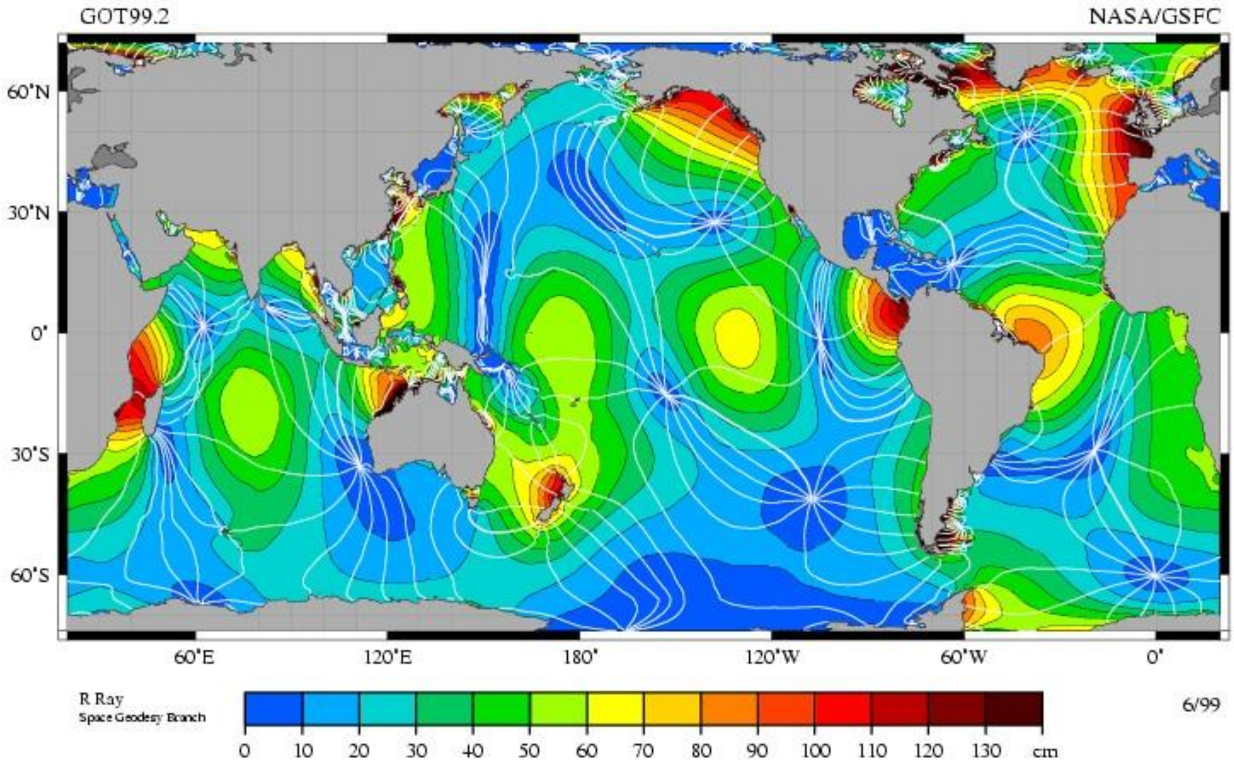
The global tides vary significantly due to differential pulls at various locations on earth, and varying shoreline configurations, as shown in the figure below.

**Figure 21: Neap Tide**




*Source: Science journals*

**Figure 22: Global Tide Ranges**




*Source: NASA/GSFC, R Ray Space Geodesy branch*

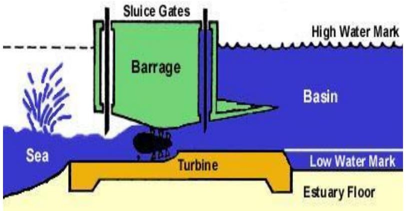
Tidal energy is the most promising and predictable marine renewable energy form as it is non-polluting, and reliable. Tidal barrages, tidal stream turbines (TST) and a variety of other machines for harnessing undersea currents are under development. The greatest quality of tidal flow is that its current is mostly constant over the water depth. Hence, tides provide the greatest opportunity to harness energy from the oceans.

There are mainly two forms of practical tidal energy harvesting methodologies:

- **Tidal Barrages:** Under this method, semi-permeable barrages are built across estuaries experiencing a high tidal range. Power is generated from tidal energy through flood generation, ebb generation and a combination of flood and ebb generation.
- **Tidal Stream Turbines:** Under this method, tidal energy is harnessed from tidal streams by means of tidal stream turbines.

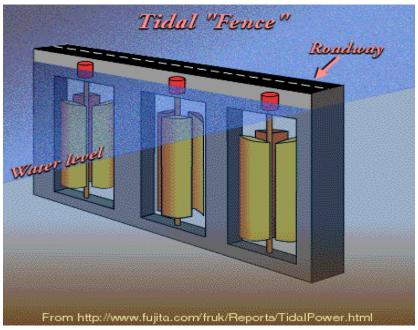
Barrages allow tidal waters to fill an estuary via sluices and to empty through turbines. Tidal streams can be harnessed using offshore underwater devices similar to wind turbines. However, all commercial implementation of tidal energy concepts employ a dam approach with hydraulic turbines. It is also normal to find only the ebb generation concept among them. Other concepts are also available for tidal energy conversion as shown in the figure below. As far as other methodologies are concerned, tidal fences and lagoons also exist. However, they are less popular and never tried on a commercial scale.

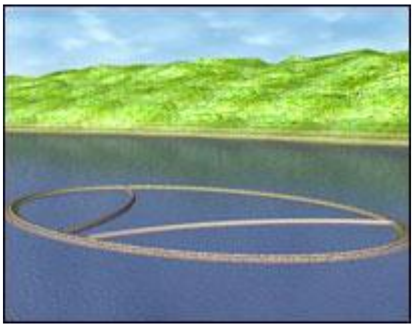
**Figure 23: Common Tidal Energy Conversion Concepts and Turbine Alternatives**



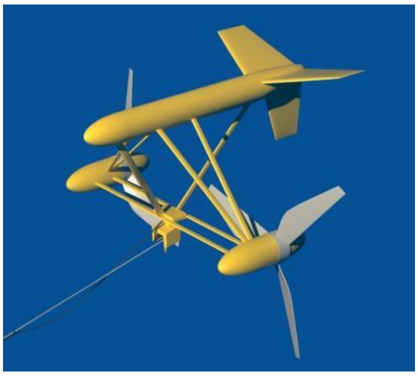

(a) Tidal barrage


(b) Tidal stream turbine

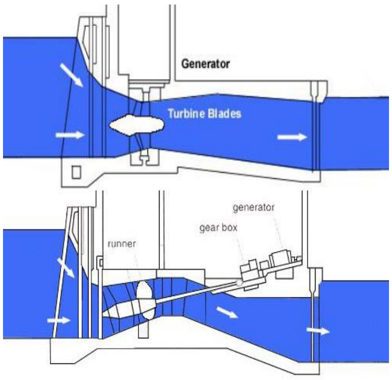


(c) Tidal fence (d) Tidal lagoon

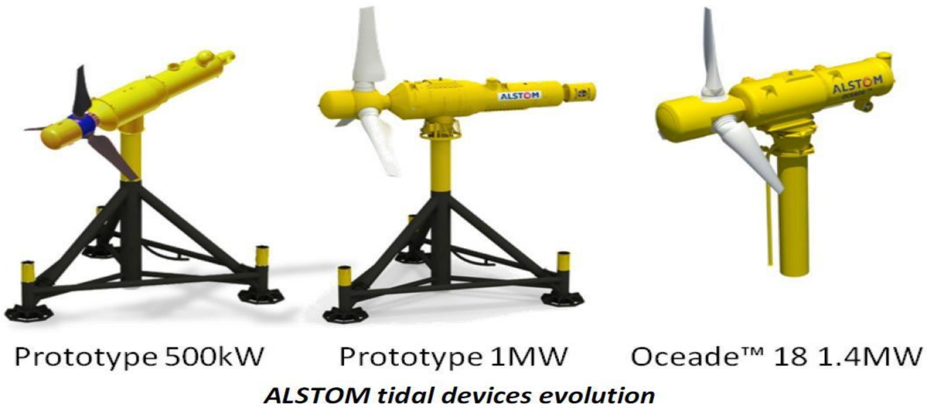


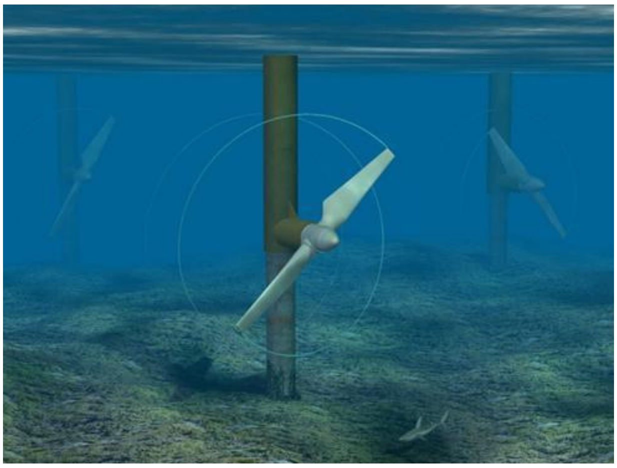
(e) Gulf stream turbine



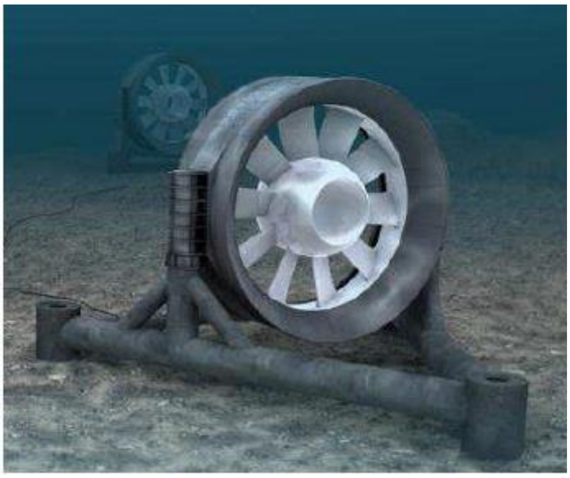

(f) Rim and Tubular turbines

**Figure 24: Variations of Tidal Stream Turbines with 16-18m Diameter (>1 MW)**





*UK Stream turbine tested in northern Scotland*



*DCNS 2 MW 16m diameter Rim type turbine*

A tidal barrage commonly consists of bulb turbines to harness tidal energy. A variety of alternatives for turbines are available in the form of rim, tubular and Davies turbines. To extract the energy from a tidal stream, a variety of stream turbines has been proposed. It includes open and rim-type turbines, as also shown in the figure above. These are still under testing stage and have not achieved commercial-scale production yet. These turbines vary in size between 16m to 18m for rated capacity of 1-2 MW. As a principle rule, a water depth of at least 35m is required to install and operate these tidal stream turbines. With a decrease in water depth, the capacity and efficiency of tidal stream turbines also reduce. Recently, Florida Atlantic University has demonstrated an efficient gulf- stream turbine which can operate in floating condition.

### 3.4.1 Tides and Tidal Datum

Any location on a shoreline encounters rise and fall of the mean sea level of the ocean on a daily basis. Hence, there is a high tide (surface water reaches its highest elevation) and low tide (lowest elevation of the surface). The vertical distance between low tides and high tides is called the tidal range and is usually attached to the maximum values. As discussed earlier, the tidal range varies, depending on the shape and depth of the coastline. In Canada‟s Bay of Fundy, a boat docked at a pier may rise as much as 20m from low tide to high tide, giving this bay a very high tidal range. Convergence of tidal energy towards landward extremities is responsible for such high tidal ranges. Since the tide arrives at a slow pace, the arriving high tide increases in level at it travels through converging coastlines. In India, the Gulf of Kutch, the Gulf of Khambat and the Sundarban regions receive some of the highest ranges of tides. A semidiurnal tide has two highs and two lows in a day, whereas a diurnal tide has one high and one low in a day.

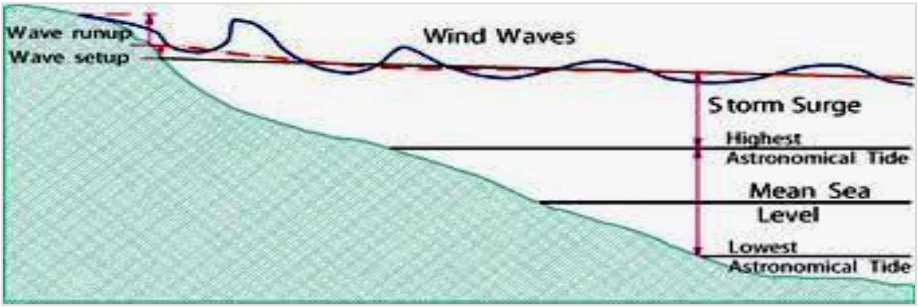
#### 3.4.1.1 Tidal Datum

All the activity in the ocean depends on the reference water levels. It is very important for the engineers to understand chart and survey datums in use in the project area. Tidal datums are site-specific and are used as references to measure local water levels. Datums are referenced to fixed points known as benchmarks so that they may be recovered when needed. Tidal datum forms the basis for establishing privately owned land, state-owned land, territorial sea, exclusive economic zone, and high seas boundaries. The following table enlists the key definitions of tidal datum maintained by the National Hydrographic Office of India.

**Table 7: Definitions of Tidal Datums**

| Term | Definition |
|---|---|
| **HAT (Highest Astronomical Tide)** | The elevation of the highest predicted astronomical tide expected to occur at a specific tide station over the national tidal datum epoch. |
| **MHHW (Mean Higher High Water)** | The average of the higher high water height of each tidal day observed over the national tidal datum epoch. For stations with shorter series, comparison of simultaneous observations with a control tide station is made in order to derive the equivalent datum of the national tidal datum epoch. |
| **MHW (Mean High Water)** | The average of all the high water heights observed over the national tidal datum epoch. For stations with shorter series, comparison of simultaneous observations with a control tide station is made in order to derive the equivalent datum of the national tidal datum epoch. |
| **MTL (Mean Tide Level)** | The arithmetic mean of mean high water and mean low water. |
| **MSL (Mean Sea Level)** | The arithmetic mean of hourly heights observed over the national tidal datum epoch. Shorter series are specified in the name, e.g., monthly mean sea level and yearly mean sea level. |
| **MLW (Mean Low Water)** | The average of all the low water heights observed over the national tidal datum epoch. For stations with shorter series, comparison of simultaneous observations with a control tide station is made in order to derive the equivalent datum of the national tidal datum epoch. |
| **MLLW (Mean Lower Low Water)** | The average of the lower low water height of each tidal day observed over the national tidal datum epoch. For stations with shorter series, comparison of simultaneous observations with a control tide station is made in order to derive the equivalent datum of the national tidal datum epoch. |
| **LAT (Lowest Astronomical Tide)** | The elevation of the lowest astronomical predicted tide expected to occur at a specific tide station over the national tidal datum epoch |
| **Storm surge** | Temporary water level increase (surge) due to persistent action of wind over water, as during cyclones |

**Figure 25: Sketch of Tide-Induced Water Levels at Shoreline**




*Source: CSIRO and BOM 2007*

## 3.4.2 Major Operational Tidal Plants

About four power plants are in operation with capacity varying from 1 MW to 254 MW. As per the study, all four have constructed tidal barrage to harness the tidal energy. The details of the major plants are given in the table below.

**Table 8: Details of Operational Tidal Power Plants**

| Name | Technology | Capacity (MW) |
|---|---|---|
| Shiwa Lake Tidal plant, South Korea | Tidal Barrage | 254 |
| La Rance Tidal power plant, France | Tidal Barrage | 240 |
| Annapolis Royal tidal plant, Canada | Tidal Barrage | 20 |
| The Jiangxia Tidal power station, China | Tidal Barrage | 3.2 |
| The Kislaya Guba Tidal facility, Russia | Tidal Barrage | 0.4 |

*Source: CRIS Analysis*

The La Rance Tidal Barrage in France with a capacity of 240 MW was commissioned in 1966 and is the oldest plant under operation. The Sihwa Lake Tidal power plant has a slightly higher capacity of 254 MW and was commissioned in 2011. The details of the La rance and Sihwa tidal plants of France and South Korea respectively are provided below.

### 3.4.2.1 La Rance Tidal power plant

The power plant is located on the estuary of the Rance River in Brittany, France. Tidal energy is harnessed using a barrage of length 750m that extends from Brebis point in the west to Briantais point in the east. The basin area is an estuary with an area of 22.5 km$^2$. The maximum tidal range available in this location is 13.5 m and the mean range is 8m. Power is generated by 24 turbines of capacity 10 MW each, amounting to 240 MW peak generating capacity. Ebb generation is used as the means of generating power. The annual generation is approximately 600GWh. The plant is currently operated by Électricité de France. The barrage construction has led to frequent siltation which has to be removed by dredging. There had also been minor environmental impacts seen in the vicinity. A view of La Rance Tidal Barrage is shown in the figure below.

**Figure 26: La Rance Tidal Barrage**

### 3.4.2.2 Sihwa Lake Tidal Power Station

Sihwa lake Tidal power station is the largest tidal power plant in operation till date, located in South Korea. The sea wall constructed for flood mitigation and agricultural purposes is used as a tidal barrage. The original basin area was 43 $Km^2$ but got reduced to 30 $Km^2$ due to land reclamation. The plant has 10 submerged bulb turbines of capacity 25.4 MW amounting to 254 MW peak generating capacity. The annual production of the plant is approximately 552.7 GWh. The power is generated only during ebb tide and sluiced during flood tides. The mean operating tidal range is 5.6 m with a spring tidal range of 7.8 m. The plant is operated by the Korean Water Resource Department.

Figure 27: Shiwa Lake Tidal Barrage

## 3.4.3 Energy Harnessing from Tides

### 3.4.3.1 New Technologies

Tidal energy can be harnessed using tidal range by constructing barrage or lagoons. Turbines in the barrier or lagoon generate electricity as the tide floods into the reservoir; water thus retained can then be released through turbines, again generating electricity once the tide outside the barrier has receded. This well-proven concept of tidal barrage was implemented at La Rance, Brittany, France and the Shiwa Tidal Power Station, Korea. The details of these projects have been brought out in earlier sections. The major disadvantage of this concept is the impact on the environment due to possible submergence of large regions. However, these effects could be considered at the time of feasibility and „Environmental Impact Assessment" (EIA) studies.

There has been a great interest in developing new tidal technologies worldwide. UK, USA and France have made significant investments in technologies that could be used where large currents are available. An alternate way of harnessing energy from tidal currents is to use tidal stream turbines (TST). The kinetic movement of water can drive the turbine just as wind turbines extract energy from the movement of air. The sea currents due to formation of the tides are often magnified where water is forced to flow through narrow channels or around headlands.

The classification of the tidal stream turbines is usually done on the basis of principles of operation, such as axial-flow, cross-flow and reciprocating devices. Axial flow turbines operate about a horizontal axis whereas cross flow turbine operates about a vertical axis. Many of these turbines resemble a wind turbine generator. Many pilot projects have been taken up by various manufacturers/owners. The details of the projects are provided in the table below.

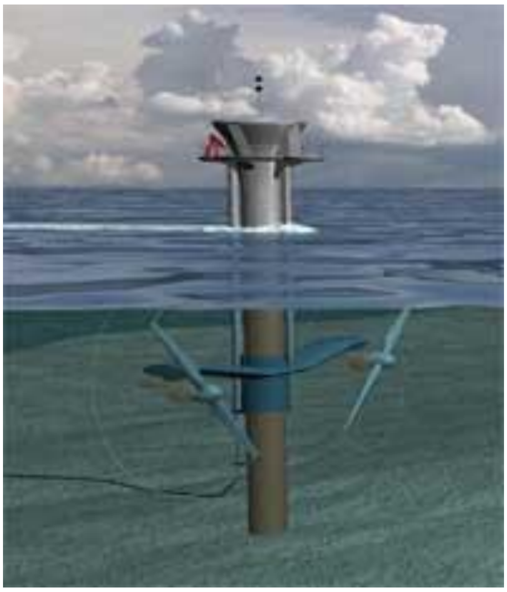
**Table 9: Pilot Projects using Tidal Stream Turbines**

| Location | Principle | Rotor Size (m) | Capacity (MW) |
|---|---|---|---|
| **SeaGen, UK** | Axial -flow | 20 | 2 |
| **Hammerfest Strom, Norway** | Axial -flow | 20 | 0.3 |
| **Hammerfest Strom, UK EMEC** | Axial -flow | 21 | 1 |
| **Atlantis, Orkney UK** | Axial -flow | 18 | 1 |
| **Vedant Powert, Roosevelt Island US** | Axial -flow | 5 | 1.05 |
| **Ponte Di Archmedia, Strait of Messina** | Cross-Flow | 6 | 1 |
| **Raz Blanchard, France** | Axial - flow rim type | 18 | 2 |
| **Ocean renewable power company, Maine.** | Cross-Flow | 2.6 | 0.25 |

*Source: CRIS Analysis*

In addition to these projects, Pulse Tidal Limited demonstrated a reciprocating device off the Humber Estuary in the UK in 2009. Several models have emerged for tidal power in recent years, including tidal lagoons, tidal fences, and underwater tidal turbines. These are still under testing stage and none of them have been deployed commercially. Among these, perhaps the most promising one is the tidal stream turbine (TST). These turbines could be placed offshore or in estuaries in strong tidal currents where the tidal flow spins the turbines, which then generates electricity. Tidal turbines have been demonstrated in waters of 30-40m depth with currents exceeding 3 m/s. Sea water is much denser than air, hence tidal turbines can be smaller than wind turbines and can produce more electricity in a given area. The below figure shows a pilot-scale tidal turbine facility; it was first installation in New York‟s East River (North America) in December 2006.

**Figure 28: Pilot Scale Tidal Turbine in North America**



*Source: www.rnp.org/node/wave-tidal-energy-technology*

As of today, TSTs remain at the demonstration level as no commercial implementations have been made. Many issues need to be sorted out before this technology can be used on a commercial scale. Developers and manufacturers of this technology are indicating positive signals which would help in finding quick solutions to the emerging issues. Some of these issues are listed below:

- **Site characteristics:** These include water depths over 35m, water currents over 3m/s and a wide channel. If a wider channel is not available, TSTs cannot be installed as the channel will be blocked for vessel traffic.
- **Cost of construction and maintenance:** TSTs need a specific industry for taking up construction. This industry is currently unavailable. Oftentimes, technologies from offshore industry will be borrowed which will result in cost escalation.
- **Environmental Impacts:** Since the TSTs are directly operated in open water, they are likely to adversely affect the environment. Some of the environmental issues are brought out in Chapter 2. These must be addressed site-wise while considering for Tidal stream turbine technology.

Because of the above aspects, TSTs remains an immature technology as of now. Hence, whenever we think of this option, all the above questions should be answered comprehensively. External links for viewing animation of tidal technologies are

1. Tidal Barrage - https://www.youtube.com/watch?v=mXEmHDQtXnw&spfreload=10
2. Tidal Stream Turbine - https://www.youtube.com/watch?v=8-sFLGMSMac&spfreload=10

### 3.4.3.2 Tidal power status in India – Earlier assessment

The ministry of New and Renewable energy (MNRE) made an assessment of the potential of tidal energy in the country. The study indicated an estimated potential of about 8000 MW with 7000 MW in the Gulf of Kambhat, 1,200 MW in the Gulf of Kutch in Gujarat, and about 100 MW in the Gangetic delta in Sunderbans in West Bengal. However, this assessment depends largely on the technology and methodology to be used. Thus, these figures can be updated continuously based on the technology used. The following table showcases the tidal energy potential as per the earlier assessment.

**Table 10: Assessment of tidal power potential in India by MNRE**

| Location | Reported Potential (MW) | Technology |
|---|---|---|
| **Kalpasar (Khambat)** | 7000 | Tidal barraging |
| **Kutch / Khumbat** | 1200 | Tidal barraging |
| **Durga Duani Creeks** | 100 | Tidal barraging |

*Source: MNRE*

The MNRE also sanctioned a project for setting up a pilot tidal power plant of capacity 3.75 MW at Durgaduani Creek in Sunderbans, West Bengal, to the West Bengal Renewable Energy Development Agency (WBREDA), Kolkata. National Hydro Power Corporation Ltd. (NHPC) was been identified as the executing agency of the project on a turnkey basis. There are recent reports that the project is likely to be shelved due to huge capital cost.

Simultaneously, a Special Purpose Vehicles (SPV) was formed by the Government of Gujarat (state government) with Atlantis to execute the project in „public-private partnership‟ format. The state government also sponsored a study for large-scale exploitation of tidal energy across the coastline of Gujarat. They also proposed the Kalpasar project in the Gulf of Khambat to exploit about 5,880 MW with an investment of about $1.7 million / MW. There is another proposal to implement tidal stream turbines in the Gulf of Kutch at a cost of $1.6 million /MW for about 50-200MW. These projects appear to have been stalled due to capital inflow and environmental issues. The details of such projects have been listed in the table below.

**Table 11: Status of tidal power activities in India**

| Location | Reported Capacity (MW) | Technology | Capital Expenditure per MW | Status |
|---|---|---|---|---|
| **Kalpasar (Khambat)** | 5880 | Tidal barrage Bulb turbines | $ 1.7 million | Ground to be broken |
| **Kutch / Khambat** | 50 (200) | Tidal stream turbine | $ 1.6 million | Concept |
| **Durga Duani Creeks** | 3.75 | Tidal barrage turbine | $ 11 million | Dropped |

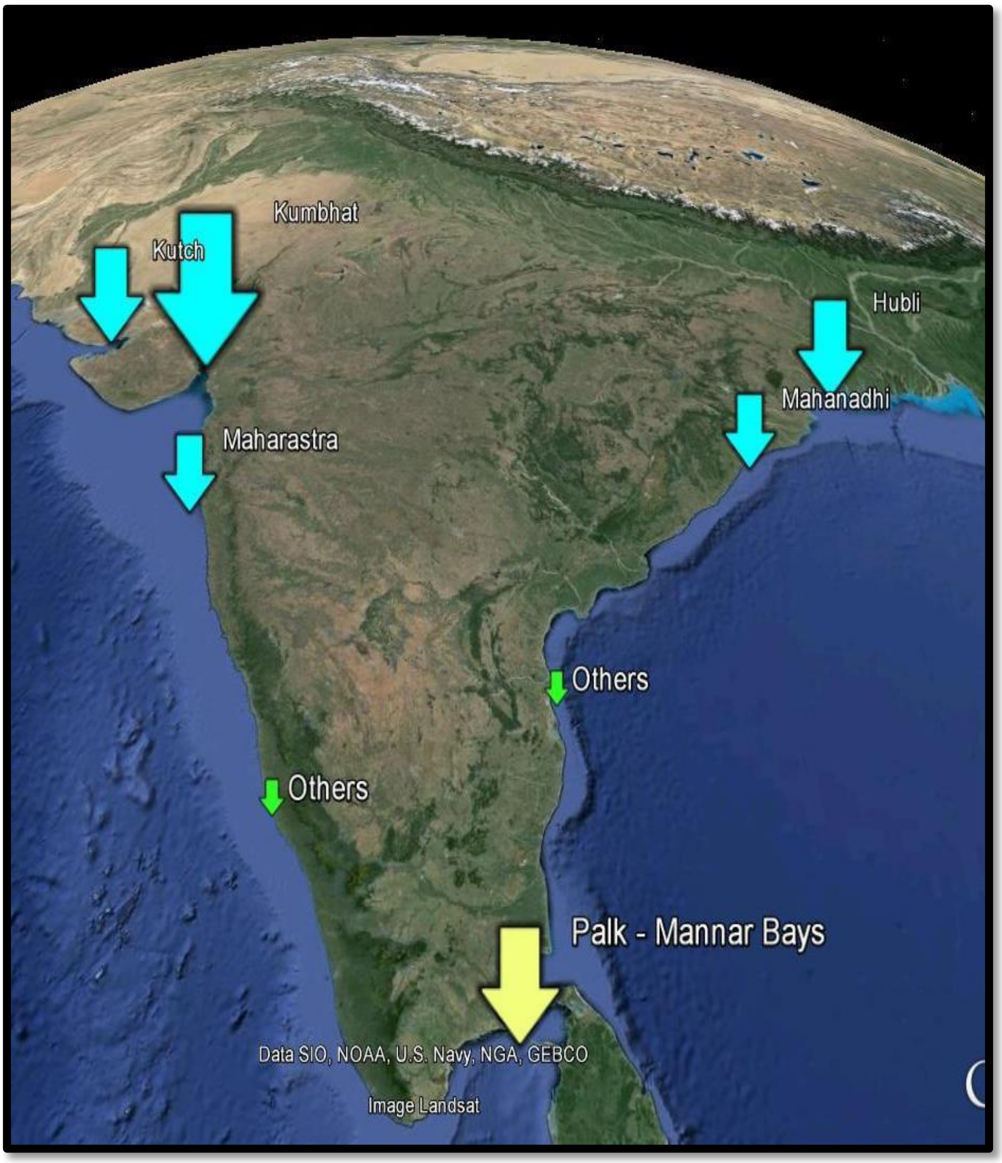
*Source: MNRE, News releases*

### 3.4.3.3 Reassessment of tidal power potential in India

The foregoing discussions suggest that the tidal power potential in India needs to be reassessed in terms of scientific evaluation and strategic planning. The following matrix brings out in clear terms the potential of tidal energy in India. The potential sites to be considered for immediate pilot projects are pointed out in below figure.

- Where there is Class-I tidal range and tidal stream, either options of developing a barrage or tidal stream farms could be chosen. However, at Khambat and Kutch, large space is also available. Hence, it is possible that both barrages and TSTs could be developed.
- However, in the Sundarbans region no water depth is available. The average depth of water is likely to be about 5-6m. Hence, it is not appropriate to think about TSTs with such water level. Instead, it is prudent to consider the option of tidal barrages.
- In other regions, currents are very weak. Thus, where Class-II-Tidal-range is available, it is highly likely that the barrage option could be considered for medium-scale power generation.
- In locations where Class-III tidal range is available, micro-power stations could be developed based on local needs.

Figure 29: Potential areas for Immediate Pilot Studies




*Source: IIT Madras Analysis*

Tidal energy is found to be concentrated in several regions of India. Although no formal study or pilot project has been reported. There is also a lack of strategic investment in this area in terms of research and development. The regions are identified, where tidal energy may be considered for development. Tidal stream conversion may be suitable for the deeper regions of Kutch and Khambat, while the shallower regions of these gulfs are suitable for barrage technology. Other regions of India including the Hooghly River / Sundarban areas may be considered for the development of medium to smaller tidal power plants.

## 3.5 Wave Energy

Wave motion is the most interesting and promising among the forms of ocean energy. During the process of wave power extraction, wave energy does not create any waste or emit $CO_2$; it leads to no noise pollution and is also environment-friendly. Unlike most renewable energy resources, wave energy can produce power throughout the year. Wave energy is highly concentrated near the ocean‟s surface in oceans worldwide. Out of the abundance energy stored in waves, only a small part of it is used for commercial electricity generation today. This largely untapped resource could play an important role not only in compensating for depleting energy sources but provide an answer to the ever-increasing demand for electricity. It is clean and more predictable than other renewable resources such as wind and solar.

This chapter deals with the details of potential sites along the Indian coastline for establishing systems to convert energy latent in ocean waves to electricity. Wave energy is produced when electricity generators are placed on the surface of the ocean in the direction of wave propagation. Prior to planning for the installation of a wave energy convertor, a detailed investigation needs to be carried out to understand available location-wise wave power potential. Available wave power depends on the wave power, its height and seasonal variation. An ideal site should have consistent power availability over the entire year. The available wave power has been evaluated from the wave characteristics for different locations along the Indian coastline. The wave power potential thus obtained is used to identify possible sites for the installation of wave energy conversion plants/devices to generate electricity from waves.

## 3.5.1 Wave Power Estimate

The wave power per unit wave front in deep water for a regular sine wave is given by,

Wave power per unit wave front, $J = \frac{\rho T (gH)^2}{64\pi} = \alpha H^2 T$ ………………….. (4.1)

In this expression, the ρ mass density of water is expressed as g, acceleration of gravity as T, the period of the wave H, and the wave height and the coefficient as $\alpha = 0.98$ kW/m$^2$. The wavelength L in terms of its period is given by the equation,

$$L = \frac{gT^2}{2\pi} = 1.56T^2 \qquad \text{……….. (4.2)}$$

For irregular waves, the wave power per unit frontage is:

$$J = \alpha_J H_{mo}^2 T_J \qquad (4.3)$$

where $\alpha_J = \alpha / 2 = 0.49$ kW/m$^2$ in deep water; $H_{mo}$ is the significant wave height; and $T_J$ is the energy transport period. $H_{mo}$ and $T_J$ are defined by means of the so-called wave spectrum. It is observed that in most cases, $H_{mo}$ is close to the average wave height of the largest 1/3rd of observed waves in a record, while, $T_J$ is approximately 20 percent longer than the zero-up crossing period $T_z$ which is defined as the average time interval between successive crossings of the mean water level as the fluid moves in the upward direction.

### Maximum Absorbed Power

The maximum power, which may be absorbed by a heaving axisymmetric point absorber is expressed as:

$$p_{max} = \frac{\rho}{2}\left(\frac{gT}{4\pi}\right)^3 H^2 = \left(\frac{L}{2\pi}\right) J \qquad (4.4)$$

$P_{max}$ is the incident power of a wave front of width equal to the wavelength divided by 2π and this width is termed as the “absorption width”. The “absorption width” is also known as “capture width”. The theoretical upper limit for the absorbed power may be approached for very small waves so that the maximum power handling capacity of the wave energy converter does not limit power take-off. Apart from the above, maximum power absorption is possible if the device produces a wave displacement oscillation of optimum phase and amplitude. The optimum phase can be achieved if the oscillating system is in resonance with incoming incident waves. The amplitude can be optimized if the loading of the oscillating system is correctly adjusted to the condition such that the magnitude of the absorbed power and the radiated power are almost the same.

**Maximum Power/Volume**

Another theoretical upper limit, derived for a heaving point absorber as reported by Budal and Falnes (1980), relates the maximum power output to the physical dimension of the devices. Based on their analysis, it is reported that the ratio of the absorbed power to the oscillating volume displacement amplitude, should be less than $\pi\rho gH/4T$ .

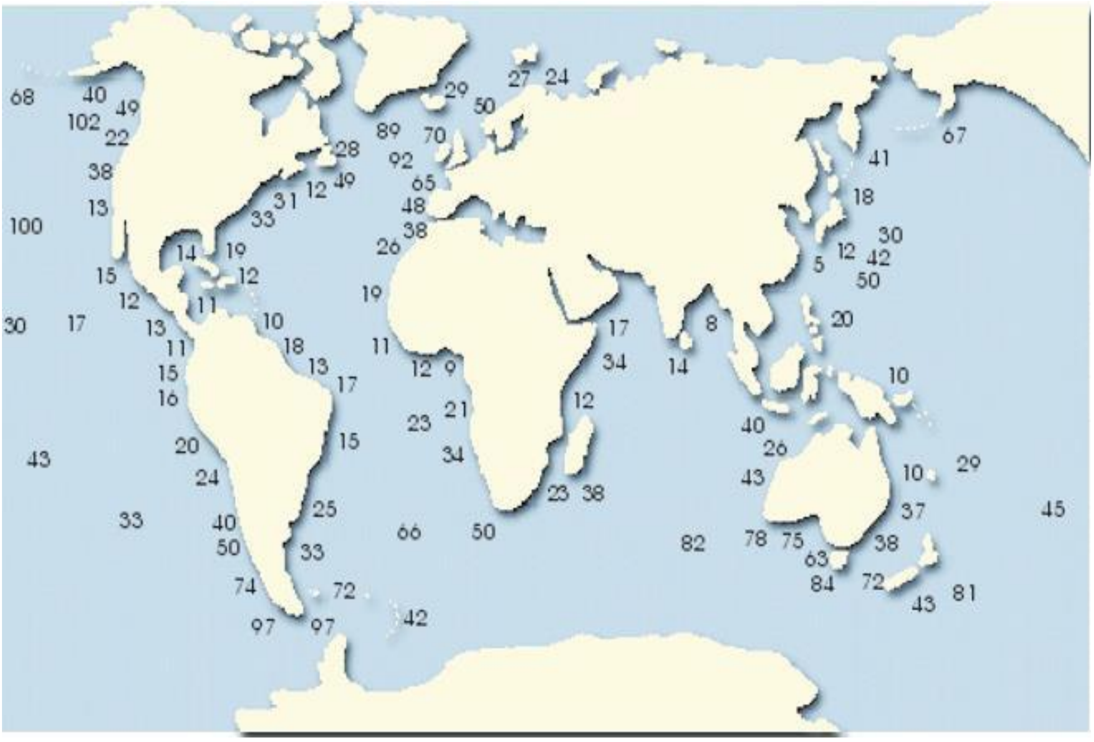
$$\left(\frac{P}{V}\right)_{\max} = \left(\frac{\pi}{4}\right)\frac{\rho gH}{T} \qquad (4.5)$$

The implication of the expression is that it may be more economical if the size of the point absorber is minimized for a selected power level, thereby exploiting only a portion of the available wave energy in the ocean, rather than converting as much as is technically possible.

### 3.5.2 Wave Energy Potential

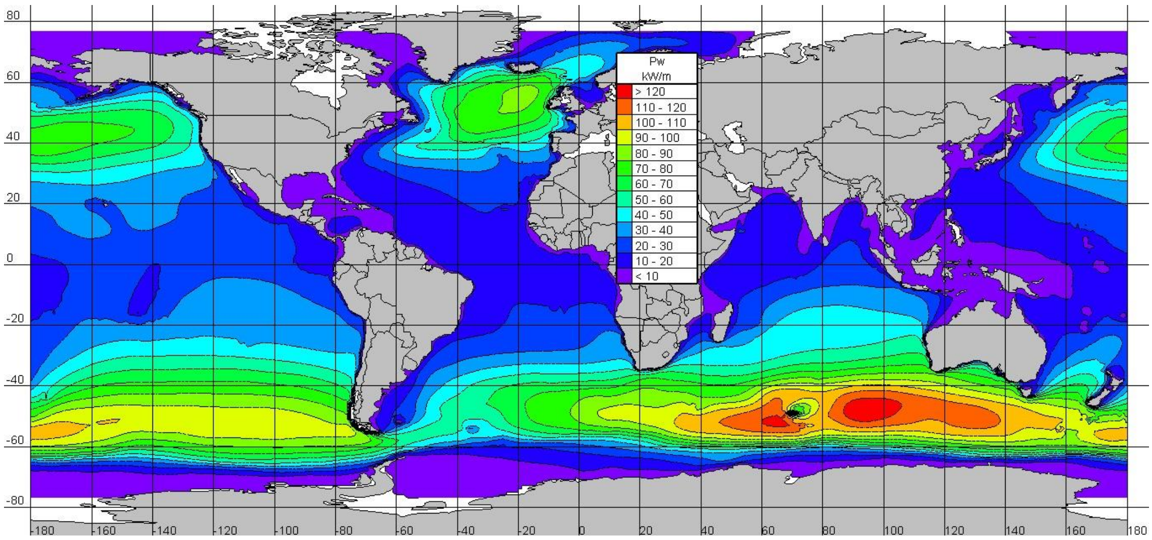
There is approximately 8,000-80,000 TW/year of wave energy in the entire ocean and on an average about 1-10 TW with each wave crest transmitting 10-50 kW per meter. The energy levels in different parts of the world are depicted in the figure below.

**Figure 30: Wave Energy levels around the globe**




From an investigation of global wave energy resources, Cornett (2008) derived from analysis of wave climate predictions generated by the WAVEWATCH-III (NWW3) wind-wave model of Tolman (2002) spanning a 10 year period from 1997 to 2006. The global distribution of annual mean wave power thus derived is presented in the following figure.

**Figure 31: Global Annual Mean Wave Energy Levels**




*Source: Cornett, 2008*

The annual mean wave power is the highest in the higher latitudes of the southern hemisphere (between 40°S and 60°S), particularly in the southern Indian Ocean around the Kerguelen Archipelago and near the southern coasts of Australia, New Zealand, South Africa and Chile; in the North Atlantic south of Greenland and Iceland and west of the U.K. and Ireland; and in the North

Pacific, south of the Aleutian Islands and near the west coast of Canada and the U.S. states of Washington and Oregon. The maximum annual mean wave power in the southern hemisphere is ~125 kW/m, found southwest of Australia near 48°S,94°E. In the northern hemisphere, the annual mean wave power south of Iceland exceeds 80 kW/m around 56°N,19°W, while the maximum in the North Pacific is ~75 kW/m, found near 41°N,174°W. It is important to note that wave power estimates presented herein describe the energy flux due to wave propagation, and that only a fraction of the energy flux available at any site can be captured and converted into more useful forms of energy. It is also important to recognize that these estimates are less reliable in shallow coastal waters.

### Indian Scenario

One of the earliest works reported on the distribution of wave power potential along the Indian coast is credited to Professor Narasimha Rao and Sundar (1982) of IIT-Madras. They employed data gathered from the National Institute of Oceanography, NIO. The data was collected from ships and Indian daily weather reports covering the period 1968 to 1973. The season-wise distribution of mean wave height, wave period and power potential along the Indian coast are reported in the table below.

**Table 12: Wave Power Potential along the Indian Coastline**

| Location | South-West Monsoon | | | North-East Monsoon | | | Non-Monsoon | | |
|---|---|---|---|---|---|---|---|---|---|
| | Wave Height (m) | Wave Period (sec) | Wave Power kW/m | Wave Height (m) | Wave Period (sec) | Wave Power kW/m | Wave Height (m) | Wave Period (sec) | Wave Power kW/m |
| 10-15° N and coast-85° E(off madras) | 1.71 | 5.80 | 16.62 | 1.53 | 5.86 | 13.44 | 1.14 | 5.5. | 7.00 |
| 15-20° N and coast-85 E(off Visakhapatnam) | 2.04 | 8.25 | 33.65 | 1.60 | 6.28 | 15.75 | 1.24 | 7.10 | 10.70 |
| 20-25 °N and coast-85-95E(off Kolkata) | 1.96 | 7.66 | 28.84 | 1.33 | 8.01 | 13.88 | 1.72 | 6.51 | 18.87 |
| 5-10° N and coast-75-80° E(off cape comorin) | 1.78 | 6.29 | 19.52 | 1.22 | 5.35 | 7.80 | 1.29 | 5.46 | 8.90 |
| 10-15° N and coast-70°E (off cochin) | 2.03 | 6.77 | 27.34 | 1.03 | 5.05 | 5.25 | 1.01 | 5.38 | 5.37 |
| 15-25° N and coast-70° E(off Bombay) | 2.63 | 6.93 | 46.98 | 1.00 | 5.00 | 4.90 | 1.01 | 5.25 | 5.24 |

*Source: NarasimhaRao and Sundar, 1982*

Wave energy is certainly one such alternative, with an estimated worldwide power of 20,000 TW/year. In India, the harnessable potential wave power is approximately estimated as 40GW. Even harvesting at least 10-20% of this energy would be a great achievement considering the persisting energy demand.

### 3.5.3 Harnessing Wave Energy

Wave energy can be harnessed through one of the three energy conversion processes mentioned below:

- **Primary Conversion**: This is the first level wherein wave energy is gained by an oscillating system. The examples for these types of systems are a floating body, an oscillating solid element or oscillating water within a structure. The oscillating systems should be capable of storing some kinetic and/or potential energy extracted from the wave.
- **Secondary Conversion**: This is the second level of stored energy converted into some useful form. This level involves utilization of drives and control systems like devices for level control and power take-off which include controllable values, hydraulic rams and pneumatic components as well as electronic hardware and software. This secondary conversion is obtained by converting the kinetic/potential energy to rotational energy by means of a turbine thereby resulting in the rotation of a shaft.
- **Tertiary Conversion**: This is the last and final level in which the rotary motion power is transferred to electric generators which converts the harnessed power into electricity.

#### 3.5.3.1 Wave Energy Converters

Wave energy converters can be classified on the basis of:

a. Horizontal size and orientation;

b. Location with respect to coastline; and

c. Location with respect to mean water level.

**A. Classification based on horizontal size and orientation**

- **Point absorbers** are devices that are very small compared to a typical wave length and are termed as point absorbers. This type of system whose size is small compared to the typical wavelength has a typical power rating of a few hundred kilowatts. Hence, a large power plant would consist of hundreds or perhaps thousands of such units, which need to be dispersed in a very long and relatively narrow array along the coast.
- **Line absorbers** are counterpart of point absorbers and are elongated floating structures. These are systems of length comparable to or larger than one typical wavelength. They are further classified as terminators and attenuators. A wave energy line absorber is a terminator if it is aligned along the prevailing direction of wave crests and behaves as an attenuator if it is aligned normally to the prevailing wave crests.

**B. Classification based on different locations with respect to the coastline**

Wave energy devices may be located onshore, near shore or offshore. Onshore wave energy devices are normally placed on the coastline, over a cliff, while the near shore wave energy devices are located in shallow waters which are normally within 10-15 km distance from the coastline, and offshore systems are deployed in deep waters.

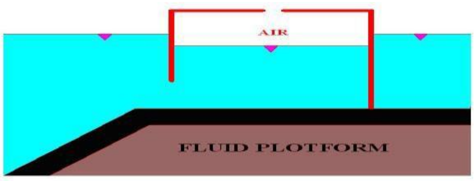
**C. Classification based on locations with respect to the mean water level**

Normally wave energy converters are found partly above and partly below the mean water level. Some forms of wave energy converters are completely submerged and placed on the seabed below the mean water level. The type of near-shore and offshore devices are moored in a freely floating mode on the free surface or with partial submergence.

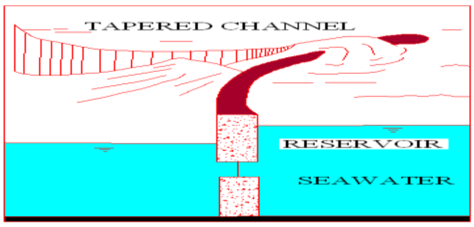
### 3.5.3.2 Conversion Process

The different process by which energy in waves can be converted to electrical energy was discussed by Hagerman (1995) and later modified by Brooke (2003). The variation from one concept to another depends on the mode of oscillation for energy absorption and type of reaction point. These oscillations like heave, surge, pitch and yaw or combinations of these motions are utilized for the absorption of energy, as shown in shore-based, near shore and offshore devices in the following figures respectively.

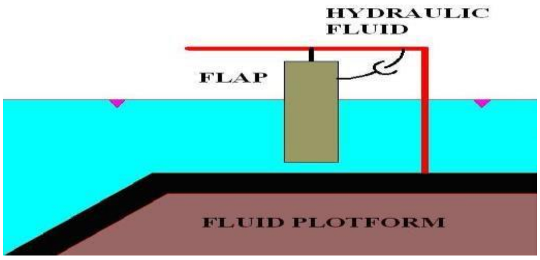
**Figure 32: Classifications of Wave Energy Devices (Onshore)**




**Fixed oscillating water column**



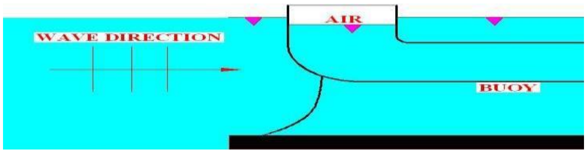

**Reservoir filled by wave surge**



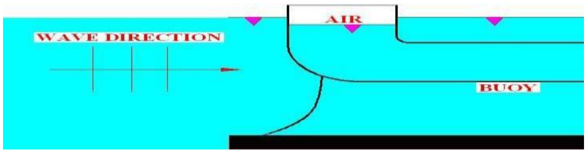

**Pivoting flaps**

*Source: IIT Madras*

**Figure 33: Classifications of Wave Energy Devices (Near Shore)**

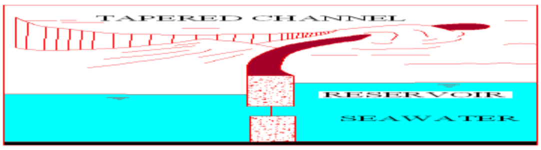



Freely floating oscillating water column (**Backward bent duct buoy, BBDB**)

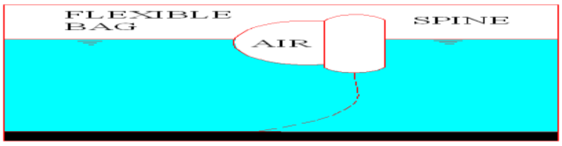



Moored floating oscillating water column (**Backward bent duct buoy, BBDB)**

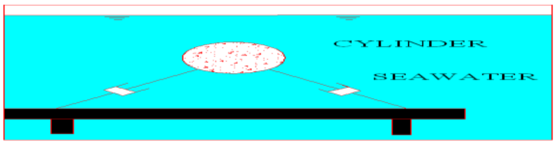

Bottom mounted oscillating water column



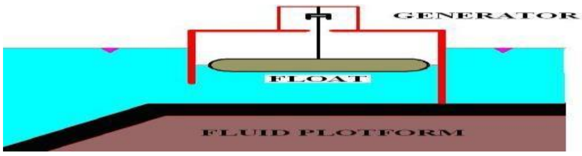

Reservoir filled by direct wave action




Flexible pressure device



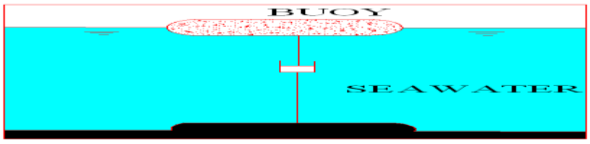

Submerged buoyant absorber with sea floor reaction



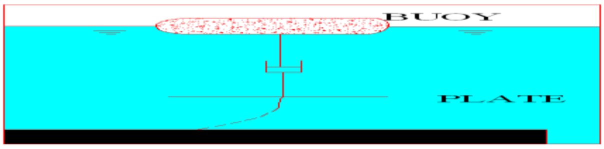

Heaving float in bottom mounted or moored floating caisson

*Source: IIT Madras*

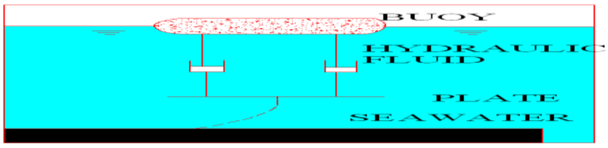
**Figure 34: Classifications of Wave Energy Devices (Offshore)**



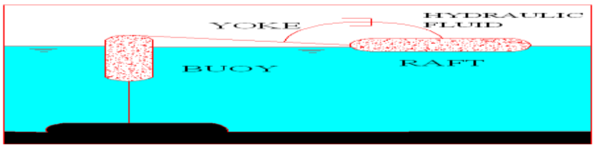

Freely heaving float with sea floor reaction point



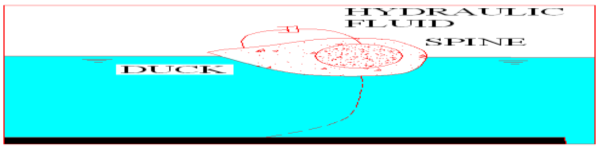

Freely heaving float with mutual force reaction



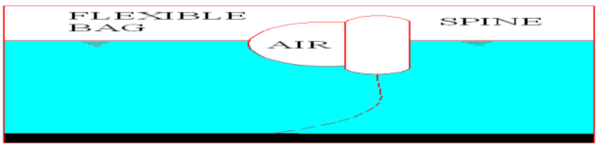

Countering float with mutual force reaction



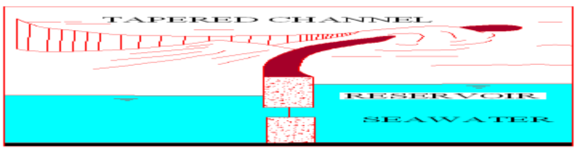

Countering float with sea floor reaction point




Pitching float with mutual force reaction




Flexible bag with spine reaction point




Reservoir filled by direct wave action

The illustrations show the various processes involved in the absorbing member which in turn reacts against fixed points on land or sea-bed-based structure, or against another movable force-resisting structure. For example, heave forces may be allowed to react against a submerged horizontal plate. The wave forces may also be allowed to react against a long spine. The resultant action of wave force is the oscillatory motion of the absorbing member. The product of wave force and corresponding motion represent absorbed wave energy. Basically, the generic types of wave energy harnessing schemes are illustrated in the above figures.

One of the earliest floating devices is the backward bent duct buoy (BBDB) that utilizes a long horizontal water-filled duct held up by a float on the water surface with opening of the duct facing away from the incident waves. The duct is connected to a vertical chamber like an oscillating water column device and the oscillation of the air / water interface drives an air turbine. Lighter buoys operating in shallower waters adopt the BBDB design. The details of the characteristics of BBDB have been discussed by Seymour (1992).

The quest for energy source during the cold war period was met by tapping energy from ocean waves. In India, power generation from ocean waves was considered as an efficient source to meet the energy demands and Ocean engineering centre of IIT Madras carried out preliminary studies in 1982. India has a 7500 km of coastline which is capable of generating 40 GW power from waves. However the capacity has increased by 1 GW as per the current sea conditions.

Vizhinjam was chosen as the first site to put up oscillating water column in the world. The water depth available at this site is 15m. The wave conditions are 1.5 to 1.8 m wave height and 6-8 s wave period. The plant was built in 1991 after investing Rs. 99 lakhs. The plant was to generate 150 kW of electricity on a continual basis that would be transferred to state grid. The amount of power generated varied considerably. During April – November the plant would generate only 75kW, and an even lesser 25kW from December – March. The plant used to work at its maximum level only during monsoon months. The plant was out of use for a long time and later on in 2004 NIOT took up the project to revive it to desalinate ocean water. It was proposed that 10,000 liters of water will be treated per day by the plant with reverse osmosis process but that project was not successful.

Finally Vizhinjam wave energy plant was completely decommissioned and handed over to the Harbor Department in 2011.

**Figure 35: Vizhinjam project in India**

*Source: IIT-Madras*

### 3.5.4 Wave Energy Devices

Depending on the type and location with respect to the coast and offshore, a number of devices have been and are being developed to extract the wave energy for conversion into electricity. The devices are referred to as the oscillating water column, hinged contour device, buoyant moored device and overtopping device.

- The **oscillating water column** device has a chamber with its one end open to the sea and the other end vented to an air turbine. A propagating wave crest acts as a piston and compresses the air inside the chamber, thus forcing it out through the turbine. When the wave trough is present in the chamber, air is sucked back through the turbine. Hence, a turbine that can rotate in the same direction irrespective of the direction of air flow is necessary to drive an alternator in order to generate electricity, on both cycles. Such a turbine is called "Wells turbine."
- The **hinged contour device** comprises a series of articulated floating sections moored to the sea bed. Following the contours of the waves, the movement of the hinges linked to hydraulic rams, drive hydraulic motors which in turn drive alternators to produce electricity.
- The **buoyant moored device** basically is a floating type with the main structure that is responsible for the conversion of energy in ocean waves to electrical will undergo motion as per the wave motion. The device is anchored to the sea floor. Various mechanisms are employed to generate electricity via turbines. The basic mechanism involved is the application of hydraulic pumps or pumps supplying seawater under pressure in order to drive the turbines.
- The **overtopping device** has a ramp over which the waves propagate and overtop creating a head of water that could probably be used to run a turbine. These devices are usually floating types but can also be of fixed type.

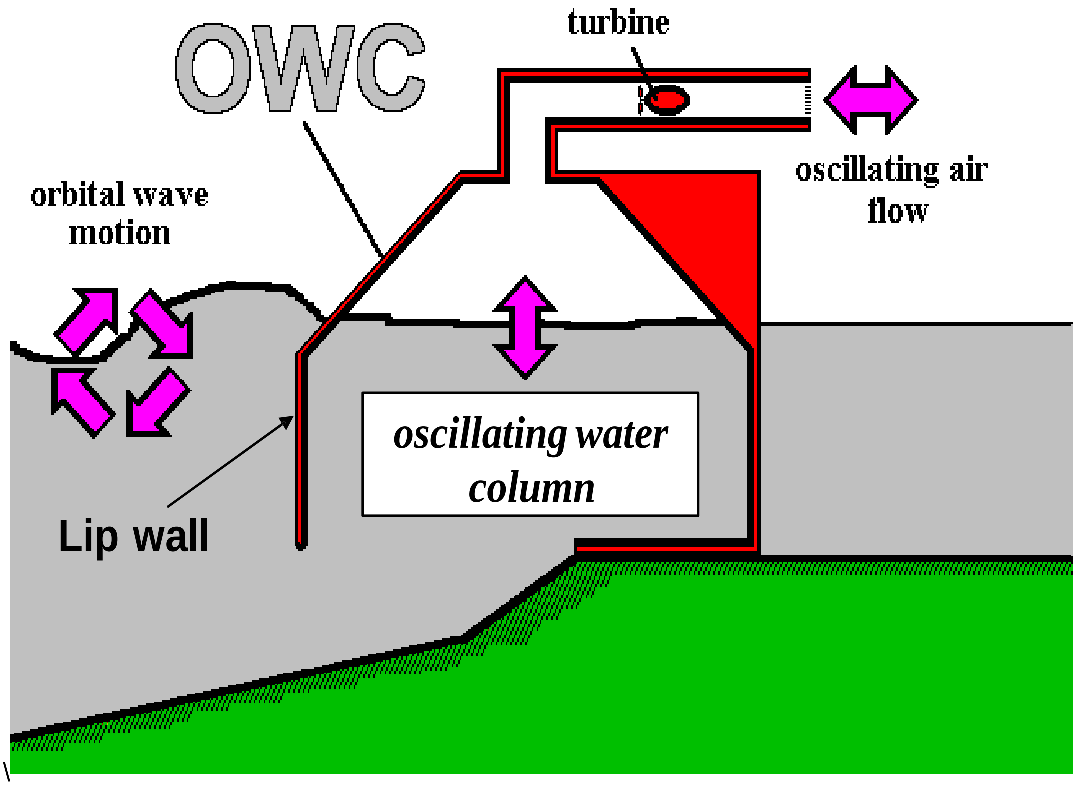
### 3.5.5 Wave Energy Device Developments

A number of new ocean energy companies have evinced keen interest in the development of new devices/technologies. A few examples of the devices are the Pelamis, the Archimedes Wave Swing and the Limpet. The plan is to increase the worldwide ocean energy harvesting capacity to 6MW in the near future. Till the last decade, the installed capacity (around the world) was about 1 MW, mainly from demonstration projects. Much of the technology comes from U.K, Japan, and Norway, with contributions from the U.S. and other countries. Research & Development in wave energy is underway in several countries around the world. A brief overview of the energy demonstration projects and their prototypes are listed below.

#### 3.5.5.1 Oscillating Water Column (OWC) Device

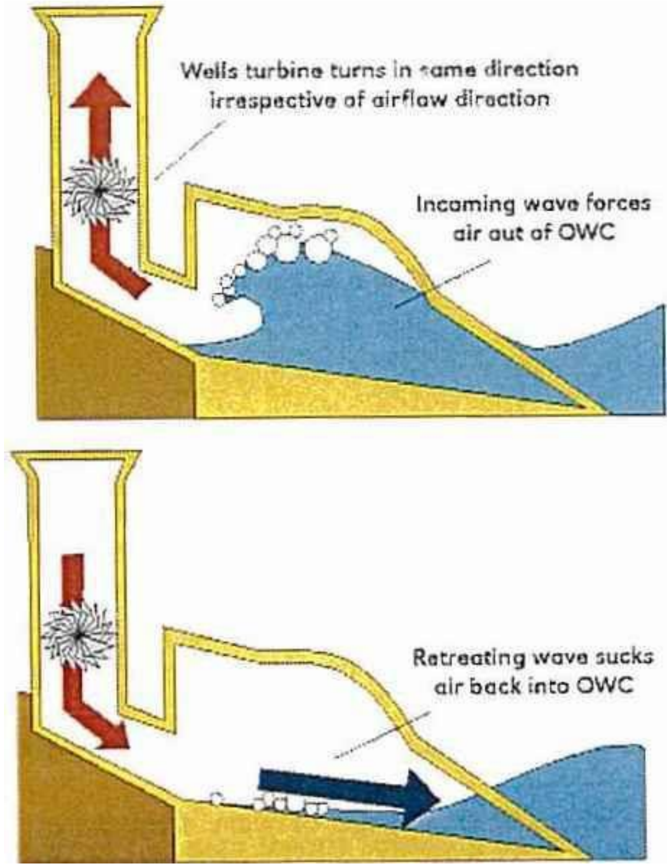
The OWC wave energy device basically consists of a rectangular chamber, a pyramidal top, which is installed on top of the chamber as shown in the following diagram.

**Figure 36: Oscillating Water Column (OWC) Device**




The rectangular chamber is open from the device floor. The lip wall allows the waves to propagate under it into the chamber. When the crest is inside the chamber, the air column above is pushed upwards through the duct and through a turbine placed in the cylindrical ducts, thus producing power. When the trough is present inside the chamber, the air column inside the chamber is pushed down and hence there is a reversal in the direction of air flow above the water column. Hence there is an oscillation of air column, the magnitude of which depends on incoming ocean waves as well as the amount of energy that can be captured by the system. A special turbine called Wells turbine mounted on top of the duct is designed to rotate in the same direction irrespective of the direction of air flow. Power is thus continuously developed irrespective of the direction of flow. A generator is coupled to the turbine that produces electricity by rotating its armature shaft, which is coupled with the turbine shaft. The working principle of OWC is shown in the figure below.

**Figure 37: Oscillating Water Column (OWC) Working Principle**




Apart from the generation of electricity by the OWC wave energy device, these types of devices can also serve as breakwater-cum-berthing facilities, coastal protection structures against erosion and calm water basins for cage culture.

Full-sized OWC prototypes were built in Norway (in Toftestallen, near Bergen, 1985), Japan (Sakata port, 1990) [Ohneda et al., 1991], India (Vizhinjam, near Trivandrum, Kerala state, 1990) [Ravindran and Koola, 1991], Portugal [Falcão, AF de O., 2000], and in UK (the LIMPET plant in Islay island, Scotland) [Heath et al., 2000]. The largest of all (2 MW), a near shore bottom standing plant (named Osprey) was destroyed by the sea in 1995 shortly after having been towed and sunk into a place near the Scottish coast. Smaller shoreline OWC prototypes (also equipped with Wells turbine) were built in Islay, UK (1991) [Whittaker, 1991], and more recently in China. The Australian company Energetech developed a technology using a large parabolic-shaped collector to concentrate the incident wave energy and a prototype was tested at Port Kembla, Australia. The following table lists the prototype installments of OWC systems.

**Table 13: Summary of OWC Devices**

| Location | Type | Rated Output | Width | Water Depth | Operation period |
|---|---|---|---|---|---|
| **Guangdong, China** | Coastal OWC | 100kW | 20m | - | Since 2001 |
| **Dawanshan, China** | Coastal OWC | 3kW | 4m | 10m | Since 1990 |
| **Isle of Islay, Scotland** | Coastal OWC (Islay 1) | 75kW | 17m | 3m | 1988-1999 |
| **Kujukuri, Japan** | OWC with pressure | 30kW | 10 × 2m | 2m | Since 1987 |

| Location | Type | Rated Output | Width | Water Depth | Operation period |
|---|---|---|---|---|---|
| | storage | | dia. | | |
| **Niigata, Japan** | Breakwater OWC | 40kW | 13m | 6.5m | 1986-1988 |
| **Toftestallen, Norway** | Coastline OWC | 500kW | 10m | 70m | 1985-1988 |
| **Sanze, Japan** | Coastal OWC | 40kW | 17m | 3m | 1983-1984 |
| **Vizhinjam, India** | Near shore close to breakwater | 50Kw | 10m | 10m | Since 1996 |
| **Pico, Portugal** | Coastal | 1MWh | - | - | Since 2005 |
| **Islay, U.K** | Coastal | 500Kw | - | - | Since 2000 |

*Source: CRIS Analysis*

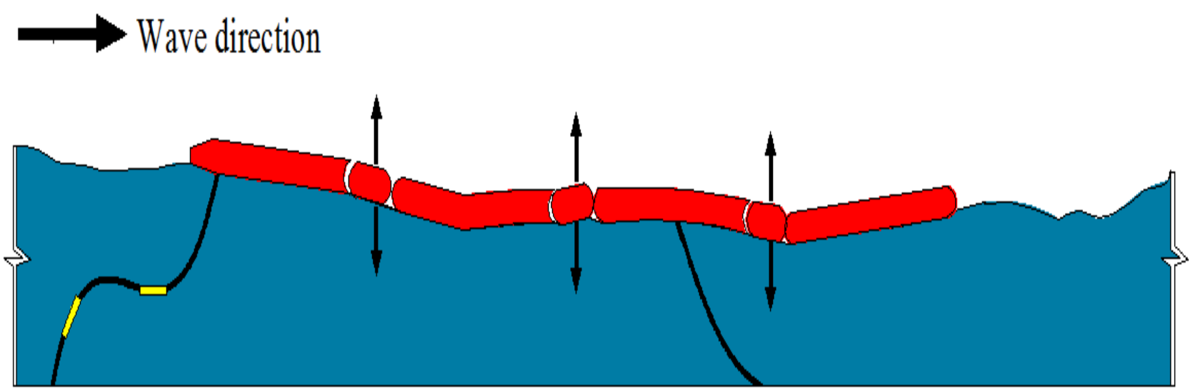
### Design Aspects

The air chamber within OWC housing must be designed with the wave period significant wave height, and wavelength characteristics of the local ocean climate in mind. If the housing is not sized correctly, waves could resonate within the air chamber. This resonating effect causes a net zero passage of air through the turbine. Ideally, the air chamber dimensions should be designed to maximize energy capture. In addition to sizing the air chamber with respect to the wave climate, the air chamber must also be conducive to air through turbine. This is best achieved with a funnel-shaped design such that the chamber narrows from the water surface level to the turbine. This will concentrate the flow through the turbine. Considerable developments have taken place in the last decade or so in the field of wave energy. Of the numerous concepts which have been tested and designed, extraction of wave energy using the oscillating water column (OWC) principle is found to be the most promising.

### 3.5.5.2 Pelamis Device

The Pelamis system is deep water, an attenuator system device that is composed of numerous long cylindrical floating systems, joined by hydraulic energy-extracting hinges. Each device is approximately 130m in length and of 3.5 m diameter. The slacked moored system allows the pelamis to orient itself perpendicular to wave crests, the most effective orientation for power extraction. Each hinge joint features four hydraulic rams, a reservoir, high pressure accumulators and motor/generator sets.

**Figure 38: Schematic alongside view of Pelamis**



Each hydraulic ram compressed or extended, high pressure fluid is transferred to an accumulator which drives a hydraulic motor which in turn drives the electrical generator. The cylindrical floats via are moved via ocean waves. One side of the hinged joint will extract power from heavy motion while the opposite site side will extract pitch energy. A small footprint of energy extraction possible from a single unit pelamis is deployed in a farm style. Each pelamis system is rated approximately efficiency at 750 kW and mechanical to electrical efficiency is quoted as 70-80%. Pelamis can be placed at water depth of 50-65 m water depth within 5-20km offshore.

External links for viewing animation of wave technologies are

1. OWC - https://www.youtube.com/watch?v=gcStpg3i5V8&spfreload=10
2. Pelamis device - https://www.youtube.com/watch?v=nH8uWOt-0z8&spfreload=10
3. Wave Dragon - https://www.youtube.com/watch?v=rgtk_Fsr0No&spfreload=10

## 3.6 List of stakeholders involved in development of technology at central and state level

Various stakeholders are involved in the development of the marine technology at the Central and State levels including universities, research centers, and private sector, and government agencies.

**Table 14: List of major stakeholders at central and state level**

| Name of Stakeholder | Head Office | Main Activities | Specialized area |
|---|---|---|---|
| **Central & State Level** | | | |
| Ministry of New & Renewable Energy | Delhi | ▪ Nodal Ministry of the Government of India for all matters relating to new and renewable energy<br>▪ Development and deployment of new and renewable energy for supplementing the energy requirements of the country | Formulation of Policies & its implementation |
| National Institute of Ocean Technology (under Ministry of Earth Sciences) | Chennai | ▪ To develop reliable indigenous technology to solve various engineering problems associated with harvesting of non-living and living resources in the Indian Exclusive Economic Zone (EEZ), which is about two-thirds of the land area of India. | Development of technologies to solve engineering problems associated with oceans |
| Indian Renewable Energy Development Agency Limited | Delhi | ▪ To promote, develop and extend financial assistance for renewable energy and energy efficiency /conservation projects with the motto : "ENERGY FOR EVER" | Financial Institution |
| CSIR – National Institute of Oceanography | Goa | ▪ Focus of research has been on observing and understanding the special oceanographic features that the north basin offers<br>▪ Data repositories of ocean related data | Data repository and research institution on Ocean Research |

| Name of Stakeholder | Head Office | Main Activities | Specialized area |
|---|---|---|---|
| Department[10] of Ocean Engineering, Indian Institute of Technology, Madras | Chennai | ▪ R&D work in areas of Ocean Engineering and related fields;<br>▪ Educational and research opportunities;<br>▪ Extension of educational facilities, training of manpower from industry in areas of Ocean Engineering | Research & Development in Ocean Engineering |
| ESSO - Indian National Centre for Ocean Information Services (under Ministry of Earth Sciences) | Hyderabad | ▪ Ocean Information and advisory services.<br>▪ Potential fishing zones, ocean state forecast, Tsunami early warnings, storm surge warnings, coral bleaching alerts, Indian seismic & GNSS network, Ocean observation networks, In-situ data, remote sensing and live access server | Information on physical, chemical, biological and geological parameters of ocean & coasts on spatial and temporal domains |
| Susi Global Research Center | Udupi | ▪ Eco-friendly research projects includes electricity generation from tidal energy, gravitational force and enhancement of power output of existing hydel projects | Tidal energy research center |
| Indian Ocean Global Ocean Observing System | Hyderabad | ▪ Promoting activities of common interest for the development of operational oceanography in the Indian Ocean region | Ocean development |
| Naval Physical & Oceanographic Laboratory | Kochi | ▪ One of the major R&D laboratories of Defence Research and Development Organization (DRDO) | Oceanography, electro-acoustic transducers, signal processing and systems engineering |
| National Center for Earth Science Studies (under Ministry of Earth Sciences) | Kerala | ▪ Promote and establish modern scientific and technological research and development studies of importance to India and to Kerala in particular, in the field of Earth Sciences | Research on atmospheric, coastal, & crustal processes, and natural resources & environment management |
| Kunjali Marakkar School of Marine Engineering, Cochin University of Science & Technology | Cochin | ▪ Educational institute to create marine engineers for marine & shipping industry | Educational Institute |
| Ocean Society of India | Kochi | ▪ Advancements and dissemination of knowledge in Science, Technology, Engineering and allied fields related to Ocean | Knowledge center |

[10] *Department has been functioning as an academic department since 1982*

| Name of Stakeholder | Head Office | Main Activities | Specialized area |
|---|---|---|---|
| Department of Meteorology and Oceanography, Andhra University | Andhra Pradesh | ▪ Teaching & research programmes in Meteorology and Oceanography | Educational Institution |
| Department of Ocean Engineering & Naval Architecture, IIT Kharagpur | Kharagpur | ▪ Teaching and training in the field of ocean engineering & marine architecture for shipping and marine related industry | Education Institution |
| DCNS Energy | France | ▪ Developer of wave and tidal energy projects<br>▪ Invested in four ocean energy technologies (OTEC, floating offshore wind turbine, tidal turbine and wave convertor)<br>▪ Developing ocean projects in India | Private Developer & Technology Provider |
| Alstom India | Noida | ▪ Turbine Manufacturer and Developer of tidal stream technology, tidal barrage and offshore wind technology based projects | Private Turbine Manufacturer and Developer |
| Atlantis Resources Limited | UK | ▪ Developer of commercial scale tidal power projects and the technologies required to economically deliver tidal current power to the grid for sale and dispatch | Private Developer and Technology Provider |
| EDF France | France | ▪ Solutions provider to power industry in generation, transmission, delivery, trading/services | Private Developer |
| **International Agencies in India** | | | |
| Agence Française de Développement (AFD) | France | ▪ Financial institution and the main implementing agency for France"s official development assistance to developing countries and overseas territories. | Financial Institution |
| KfW Development Bank | Germany | ▪ Finances and promotes sustainable change in Germany and abroad<br>▪ Finances development cooperation projects and programmes around the world on behalf of German Federal Government | Financial Institution |

# 4. Potential Assessment of Tidal and Wave Energy

## 4.1 Tidal Energy

A small brief on the progress made so far, projects, past studies on potential, and stakeholders involved in the development of technologies.

### 4.1.1 Tidal Levels along Indian Coastline

The tidal level at various locations along the Indian coastline has been measured using the National Institute of Oceanography tide table and by performing a harmonic analysis. The predictions are valid for long term as tidal magnitudes are estimated using 37 species. In case of many locations along the coastline, the first few components only determine tidal levels. Hence, the predictions are valid for a very long term nature. The following table gives the details of spring and neap tidal range for 46 locations along with details of latitude and longitude.

**Table 15: Tidal range along Indian coastline**

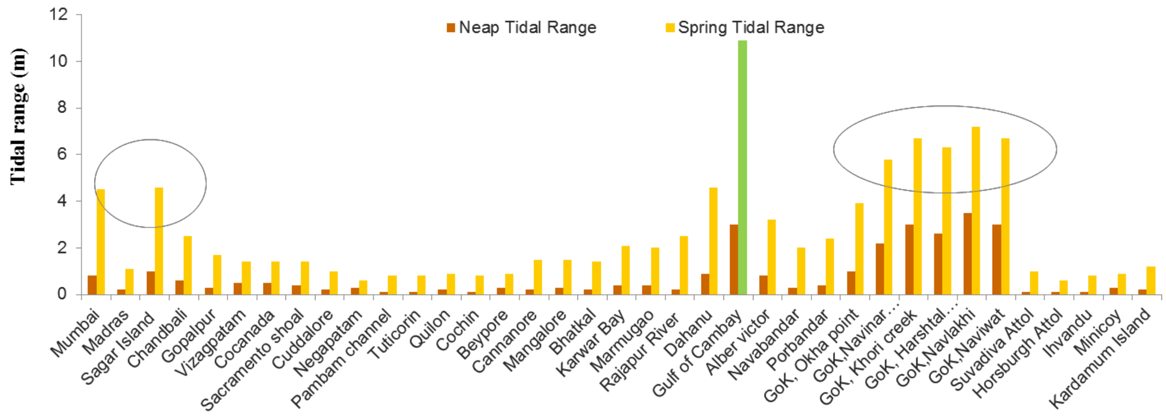
| Location | State | Latitude | Longitude | Neap Tidal range (m) | Spring Tidal range (m) |
|---|---|---|---|---|---|
| **Mumbai** | Maharashtra | 18.55 | 72.5 | 0.8 | 4.5 |
| **Madras** | Tamil Nadu | 13.6 | 80.18 | 0.2 | 1.1 |
| **Sagar Island** | West Bengal | 21.4 | 88.03 | 1 | 4.6 |
| **Malta River** | West Bengal | 20.5 | 88.3 | 0.9 | 2.9 |
| **Diamond Harbor** | West Bengal | 22.11 | 88.11 | 1.7 | 5.3 |
| **Calcutta garden** | West Bengal | 22.33 | 88.18 | 1.2 | 4.9 |
| **Shortt Island** | Orissa | 20.47 | 87.04 | 0.9 | 3 |
| **Chandbali** | Orissa | 20.4 | 86.44 | 0.6 | 2.5 |
| **Gopalpur** | Orissa | 19.16 | 84.55 | 0.3 | 1.7 |
| **Vizagpatam** | Andhra Pradesh | 17.41 | 83.17 | 0.5 | 1.4 |
| **Cocanada** | Andhra Pradesh | 16.56 | 82.15 | 0.5 | 1.4 |
| **Sacramento shoal** | Andhra Pradesh | 16.36 | 82.19 | 0.4 | 1.4 |
| **Cuddalore** | Tami Nadu | 11.43 | 79.47 | 0.2 | 1 |
| **Negapatam** | Tami Nadu | 10.45 | 79.47 | 0.3 | 0.6 |
| **Pambam channel** | Tami Nadu | 9.16 | 79.12 | 0.1 | 0.8 |
| **Tuticorin** | Tami Nadu | 8.48 | 78.1 | 0.1 | 0.8 |
| **Quilon** | Kerala | 8.53 | 76.34 | 0.2 | 0.9 |
| **Cochin** | Kerala | 9.58 | 76.15 | 0.1 | 0.8 |
| **Beypore** | Kerala | 11.1 | 75.48 | 0.3 | 0.9 |
| **Calicut** | Kerala | 11.15 | 75.46 | 0.2 | 1.2 |

| Location | State | Latitude | Longitude | Neap Tidal range (m) | Spring Tidal range (m) |
|---|---|---|---|---|---|
| **Tellicherry** | Kerala | 11.45 | 75.29 | 0.3 | 1.5 |
| **Cannanore** | Kerala | 11.51 | 75.22 | 0.2 | 1.5 |
| **Mangalore** | Karnataka | 12.51 | 74.5 | 0.3 | 1.5 |
| **Malpe** | Karnataka | 13.2 | 74.41 | 0.6 | 1.7 |
| **Bhatkal** | Karnataka | 13.58 | 74.32 | 0.2 | 1.4 |
| **Karwar Bay** | Karnataka | 14.48 | 74.06 | 0.4 | 2.1 |
| **Marmugao** | Goa | 15.25 | 73.48 | 0.4 | 2 |
| **Rajapur River** | Maharashtra | 16.37 | 73.2 | 0.2 | 2.5 |
| **Bassein** | Maharashtra | 19.18 | 72.48 | 0.9 | 4.4 |
| **Dahanu** | Maharashtra | 19.58 | 72.43 | 0.9 | 4.6 |
| **Gulf of Cambay** | Gujarat | 21.45 | 72.14 | 3 | 10.9 |
| **Alber victor** | Gujarat | 20.57 | 71.32 | 0.8 | 3.2 |
| **Navabandar** | Gujarat | 20.45 | 71.05 | 0.3 | 2 |
| **Porbandar** | Gujarat | 21.38 | 69.37 | 0.4 | 2.4 |
| **GoK, Okha point** | Gujarat | 22.28 | 69.05 | 1 | 3.9 |
| **GoK,Navinar point** | Gujarat | 22.45 | 69.43 | 2.2 | 5.8 |
| **GoK, Khori creek** | Gujarat | 22.58 | 70.14 | 3 | 6.7 |
| **GoK, Harshtal point** | Gujarat | 22.56 | 70.21 | 2.6 | 6.3 |
| **GoK,Navlakhi** | Gujarat | 22.58 | 70.27 | 3.5 | 7.2 |
| **GoK,Naviwat** | Gujarat | 23.05 | 70.2 | 3 | 6.7 |
| **Kori creek** | Gujarat | 23.31 | 68.21 | 0.6 | 3.2 |
| **Minicoy** | Lakshadweep | 8.16 | 73.01 | 0.3 | 0.9 |
| **Kardamum Island** | Lakshadweep | 11.13 | 72.46 | 0.2 | 1.2 |

*Source: IIT Madras*

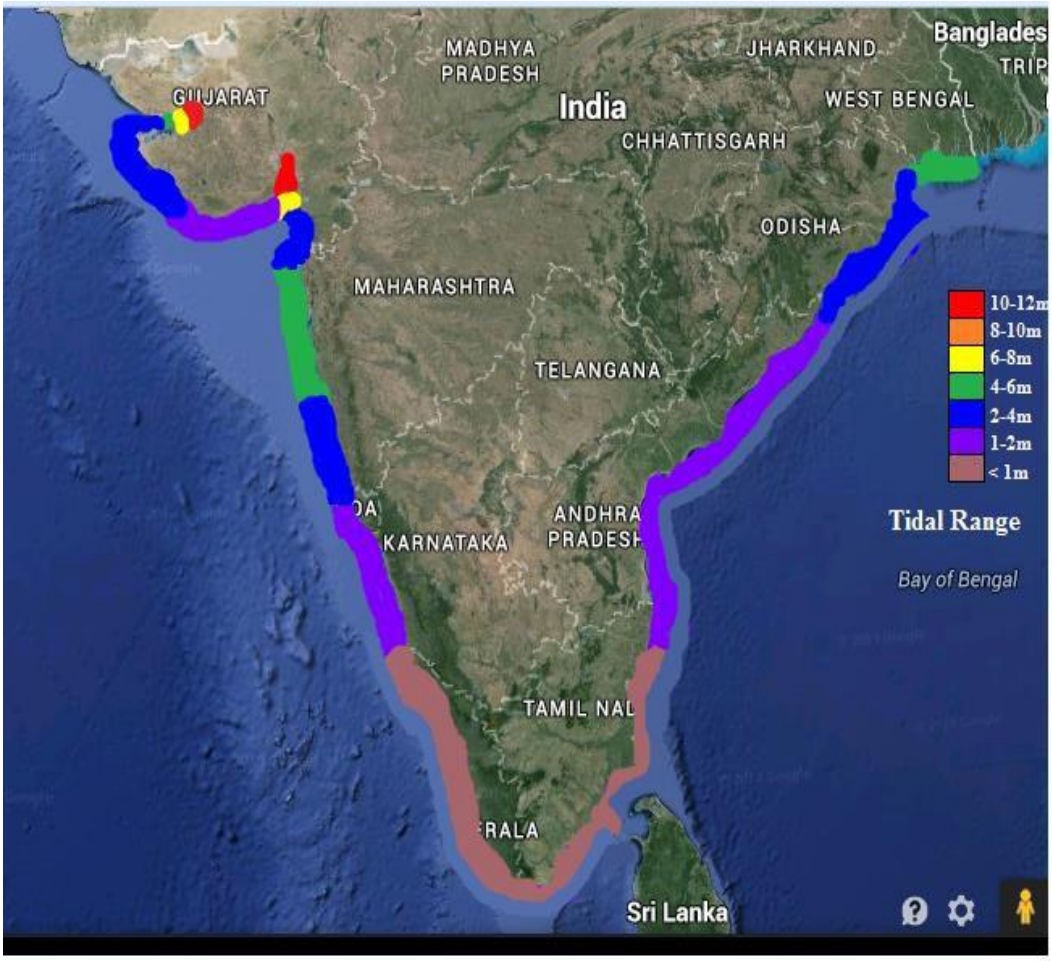
The tidal range for spring tide and neap tide for 37 stations along the Indian coastline is plotted in the following diagrams.

**Figure 39: Tidal range along Indian coast**




*Source: IIT Madras*

**Figure 40: Spring tidal range along Indian coast**




*Source: IIT Madras*

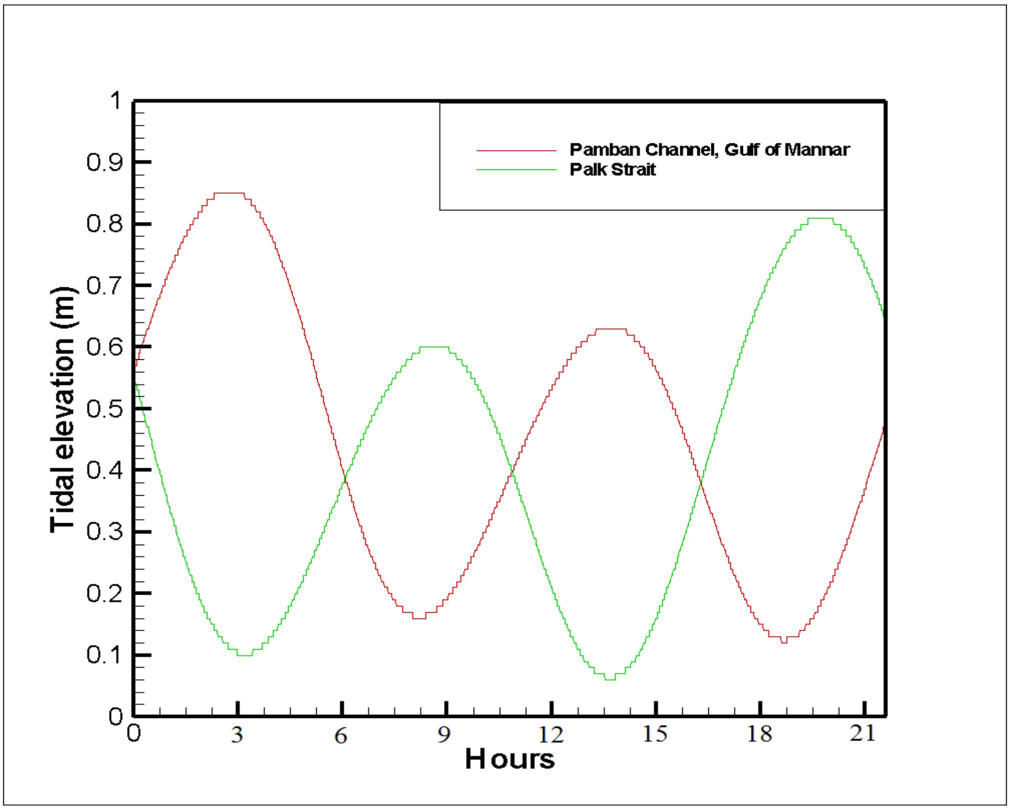
The results presented above clearly indicate that the maximum tidal ranges in India are observed in the Gulf of Kutch and Gulf of Kambhat region with a range of 10 to 11m. The tidal range observed along the Sundarbans area, which is about 5.5m in magnitude. The regions may be categorized as

Class-I-Tidal-range. Apart from these, the regions south of Gujarat and West Bengal also experience moderate tidal range of 3 to 5 m. These regions may be categorized as Class-II-Tidal-range. Creating a tidal reservoir and generating during the ebb cycle is a good option for these regions.

In the South, the tidal ranges are less. However, 1m tide can be stored in large backwater areas and micro-tidal plants can be established after conducting a detailed feasibility analysis. Some significant backwater areas are available in all the southern states. The regions may be categorized as Class-III-Tidal-range.

The Pamban channel area also has a good potential with the Palk bay to the north and the Gulf of Mannar to the south experiencing a tidal phase difference of about 6 hours as shown in the figure below. A channel could be developed in this region to make use of this naturally available advantage. Hydrodynamics of the channel could be designed in such a way as to create an assured velocity so that turbines can operate for up to 20 hours in a day.

**Figure 41: Typical Time History of Tides in Palk bay and Gulf of Mannar**




*Source: IIT Madras*

## 4.1.2 Tide-induced Coastal Currents

Currents are masses of water moving from one place to another. Tidal currents are driven by several factors. The rise and fall of the tide is the main factor for the generation of tidal currents. This rise and fall causes movement of a mass of water from high potential to low potential. The change in tidal currents over the day follows a regular and predictable pattern. Wind, if very strong, has some contribution to the coastal currents. Wind-driven currents exist near the ocean‟s surface. These currents are generally measured in meters per second or in knots (1 knot = 1.15 miles per hour or 1.85 kilometers per hour).

#### 4.1.2.1 Tidal Currents along Indian coastline

A detailed discussion on tidal current warrants extensive hydrodynamics modeling. Therefore, we bring out a general idea of the tide-induced currents here to get an idea of tidal power that can be extracted from various regions. Tidal current occurs due to the rise and fall of the tide. When a tidal current moves toward the land or an estuary and away from the sea, it “floods.” When it moves toward the sea away from the land or an estuary, it “ebbs.”

The order of tidal currents has a strong correlation with tidal range. The maximum tidal current is usually observed in locations of higher tidal range. The highest tidal currents usually occur in the Gulfs of Kutch and Khambat as well as Sundarbans regions. Usually, it is common to find currents exceeding 2m/s at most times of the day. This is generated by tidal gradients in the Kutch and Khambat regions. In the Sundarbans areas, even though the range of tide is lesser compared to that in the Kutch/Khambat regions, the fresh water flow and narrowing of channels in Hooghly can produce currents up to 3m/s most of the time. As far as tidal currents are concerned, these stretches could be categorized as Class-I-Tidal-Stream.

The currents generally exceed 2m/s in South of West Bengal and Khambat region. As tides enter the Bay of Bengal and the Arabian Sea, a general convergence is seen in the above regions which lead to good level of currents. These regions may be categorized as Class-II-Tidal-stream. Moderate currents exist in north of Tamilnadu and Kerala that are in the range of 1.5m/s to 2.0m/s. There are locations along the coast of Karnataka / Maharashtra (west coast) and along the Coromandal coast (east coast). These regions may be categorized as Class-III-Tidal-stream. The regions with currents less than 1m/s may be classified as Class-IV-Tidal-stream having weak tidal velocities.

**Table 16: Naturally occurring currents along Indian coastline**

| Coastal Region | Tidal Range | Typical Tidal Current | Stream classification |
|---|---|---|---|
| **Khambat** | 5-11m | 2.5m/s | Class-I-Tidal-stream |
| **Kutch** | 4-9m | 3.0m/s | Class-I-Tidal-stream |
| **South Gujarat / Maharashtra** | 2-4m | 1.5-2.5m/s | Class-II-Tidal-stream |
| **Karnataka / Kerala coast** | 1-1.5m | 1.5-2.0m/s | Class-III-Tidal-stream. |
| **Tamilnadu coast** | 1m | 0.8m/s | Class-IV-Tidal-stream |
| **Palk-Mannar Bay** | 1.0m | 0.6m/s | Class-IV-Tidal-stream |
| **Andhra coast** | 1-2m | 1m/s | Class-III-Tidal-stream. |
| **Orissa coast** | 2-4m | 1.5m/s | Class-II-Tidal-stream. |
| **Sundarbans / Hoogly** | 4-7m | 2-3m/s | Class-I-Tidal-stream. |

*Source: IIT Madras*

#### 4.1.2.2 Tidal potential along the Indian coastline

##### Theoretical Estimation of Energy from Tidal Barrage

The tide contains both potential and kinetic energy. The potential energy is the energy stored or available when water is available at an elevation higher than normal. This is possible during flooding tides and energy will be available during the ebbing phase. The energy available from a barrage depends on the area of the water surface impounded by the barrage and the corresponding magnitude of the tidal range. The potential energy contained in the water volume impounded in a basin, can be expressed as:

where, $E_p$= potential energy over a tide cycle; $\rho$= density of sea water (t/m3); $g$= acceleration due to the earth's gravity (9.807 m/s$^2$); $A_b$= horizontal area of the enclosed basin (km$^2$); and $\Delta h_b$= mean tidal range in the basin (m). The density of sea water varies from 1.021 to 1.030 t/m$^3$, and is typically assumed to be 1.025 t/m$^3$. The coefficient of 0.5 in above Eq. is due to the fact that as the water in the basin is released through the turbines, the water head across the dam will be reduced accordingly. The maximum available head only occurs at the moment of low water assuming that high water level is still present in the basin. It can be seen from the Equation (1) that tidal range influences greatly the value of the potential energy, and the magnitude of the mean tidal range and the value of the impounded area are the most important factors that determine the feasibility of a tidal barrage in terms of annual energy output.

### Theoretical Estimation of Energy from Tidal Currents

The tidal generators make use of the kinetic energy of the water stream which in turn will spin the turbine and drive the generator and hence produce electricity. The power that can be generated by the tidal turbine is given by Eq. (2)

where, Ek= Kinetic Energy (GW), Cp = Turbine power coefficient, g= acceleration due to the earth's gravity (9.807 m/s$^2$); as= swept area by turbine blades (m$^2$); and V= velocity of the tidal current (m/s).

### Tidal Energy Density along Various States of India

A detailed discussion on tidal ranges and currents along the Indian coastline has been presented in table below. In order to understand the real meaning of these data in terms of energy, the estimates of potential energy (PE) and kinetic energy (KE) have been tabled below.

**Table 17: Tidal Potential along Indian Coastline**

| Coastal Region | Tidal Range | Typical Tidal Current* | Ave. Available PE per sq. km (MW) | Ave. Available KE per sq.m (W) |
|---|---|---|---|---|
| **Khambat** | 5-11m | 2.5m/s | 10.9 | 2604.3 |
| **Kutch** | 4-9m | 3.0m/s | 7.2 | 4500.2 |
| **South Gujarat** | 2-4m | 2.0m/s | 1.5 | 1333.4 |
| **Maharashtra** | 2-4m | 1.5m/s | 1.5 | 562.5 |
| **Karnataka** | 1-1.5m | 1.5m/s | 0.2 | 562.5 |
| **Kerala** | 1-1.5m | 1.5m/s | 0.2 | 562.5 |
| **Tamilnadu coast** | 1m | 0.8m/s | 0.1 | 85.3 |
| **Andhra coast** | 1-2m | 1m/s | 0.2 | 166.7 |
| **Orissa coast** | 2-4m | 1.5m/s | 1.5 | 562.5 |
| **Sundarbans** | 4-7m | 2-3m/s | 7.2 | 2604.3 |

| | |
|---|---|
| ***As the tide flows in and out of an inlet / estuary** | |

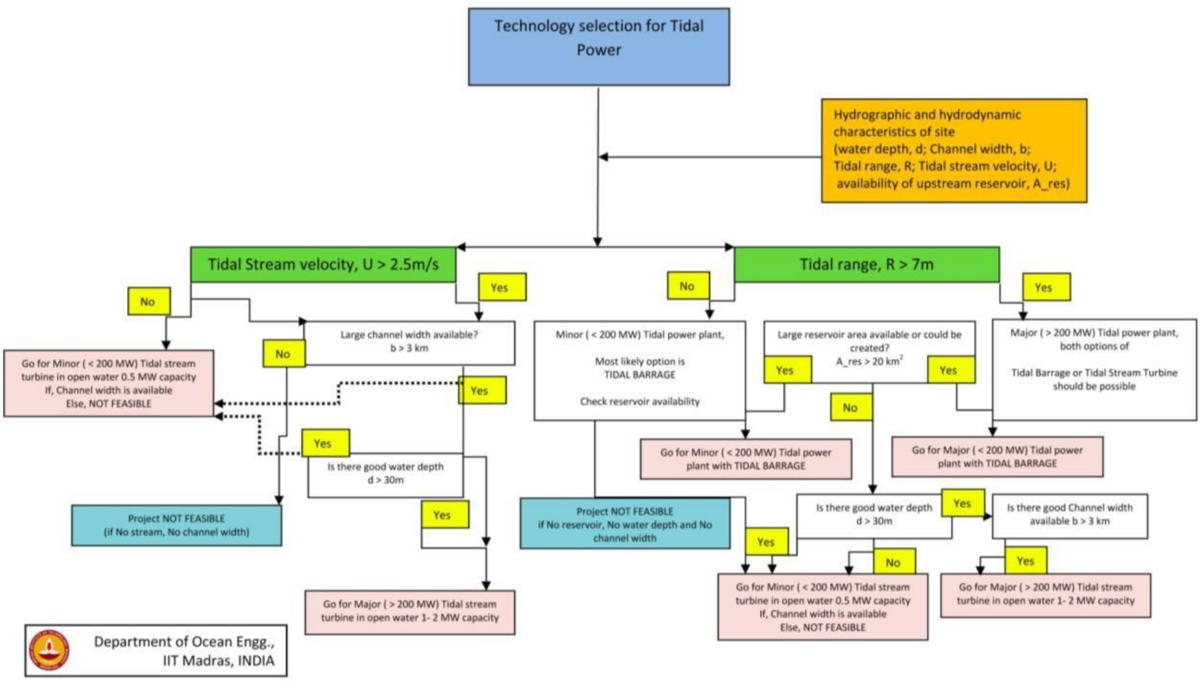
*Source: IIT Madras*

The table above presents the fact that three regions in India provide the largest concentration of energies. These are namely Khambat, Kutch and Sundarbans regions, because of their large tidal ranges. However, the table also brings out the fact that when flow velocities are enhanced at the openings on the coastline, it is possible to realize reasonably good amount of energy in terms of KE. Hence, for regions with low tidal range, the obvious choice will be to modify the flow pattern of the tidal flooding and ebbing so that reasonably good currents are generated.

### 4.1.3 Feasible Sites for Tidal Energy in India

As detailed above, tidal energy can be harnessed using various technologies from several potential locations of India. The critical parameters for assessing suitability of a certain technology depend on two critical parameters – tidal range and tidal stream velocity. This could be followed by a systematic approach to arrive at a suitable technological option (tidal barrage or tidal stream turbine). The methodology utilized for technology selection has been detailed in the following figure.

**Figure 42: Technology Selection Process for Tidal Energy**




*Source: IIT Madras*

On this basis, the feasible sites that have been identified are summarized in the table below. These options are discussed individually in the following sections.

**Table 18: Potential Tidal Energy Options Matrix**

| Location | Tidal Range | Tidal Current | Potential Option |
|---|---|---|---|
| **Khambat / Kutch** | Class-I-Tidal-range | Class-I-Tidal-stream | Barrage & Stream turbine |
| **Hooghly / Sundarbans** | Class-I-Tidal-range | Class-I-Tidal-stream | Barrage |

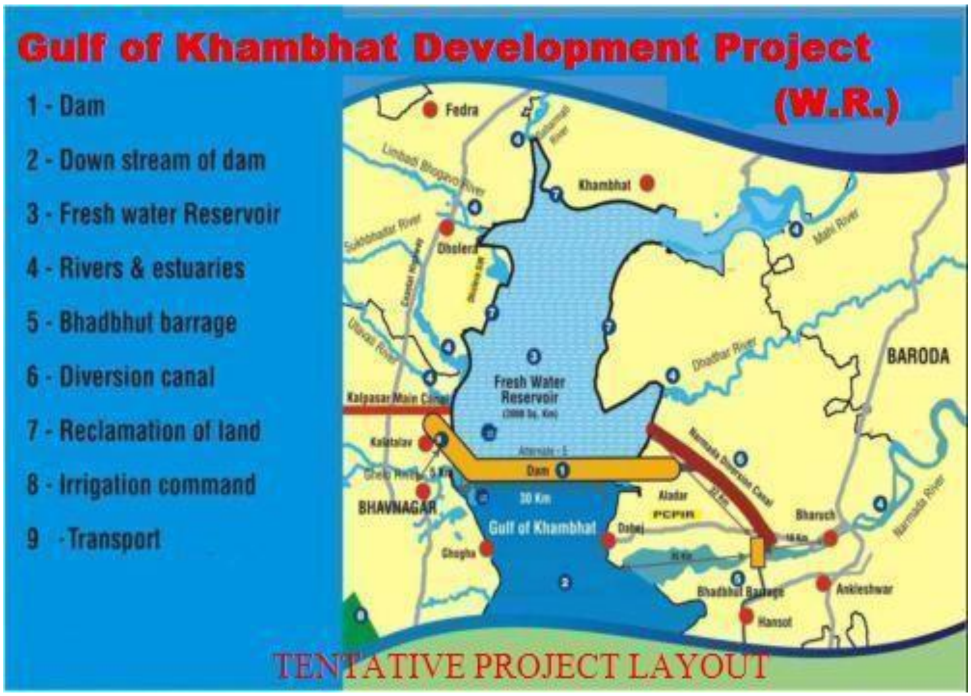
| Location | Tidal Range | Tidal Current | Potential Option |
|---|---|---|---|
| **South Gujarat / North Maharashtra / Orissa** | Class-II-Tidal-range | Class-II-Tidal-stream | Barrage |
| **Karnataka/Maharashtra/Kerala/Andhra** | Class-III-Tidal-range | Class-III-Tidal-stream | Barrage |
| **Palk-Mannar Bay** | Class-III-Tidal-range | Class-IV-Tidal-stream | Barrage |

*Source: IIT Madras*

#### 4.1.3.1 Gulf of Kambhat

The Gulf of Kambhat has a tidal range of 11m with 7m mean tidal range as discussed earlier. There is a proposal for an 8,000 MW mega power project at Kalpasaras as shown in the schematic diagram below.

**Figure 43: Gulf of Khambhat Development Project**



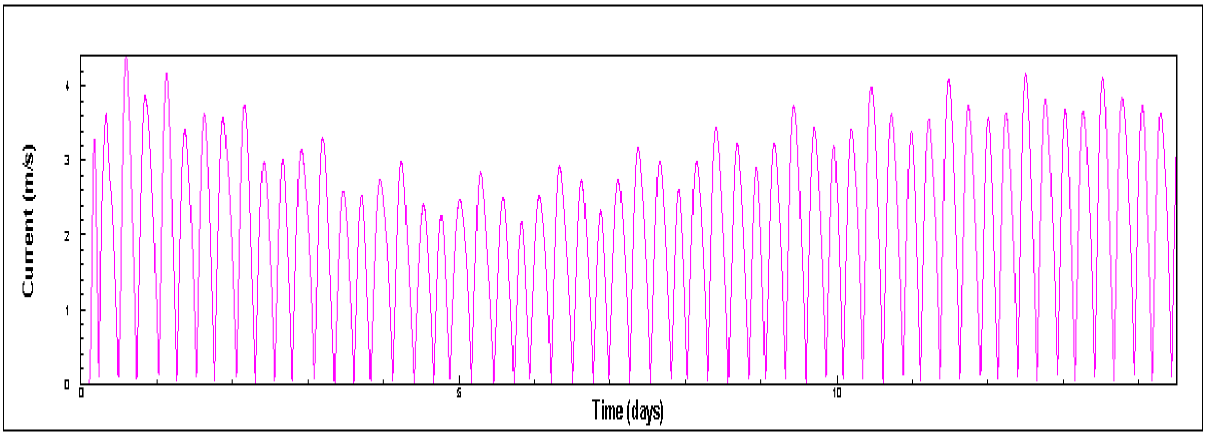

*Source: IIT Madras*

This is a barrage-based tidal project which leaves scope for the development of a stream turbines-based project in the region. However, the water depths are only reasonably good. Hence, new technologies, and smaller & efficient turbines must be designed for these areas. The two regions that have been identified are shown in the following map snapshot.

**Figure 44: Possible Locations for Tidal Stream Farm with Tidal Stream Turbines**


*Source: IIT Madras*

**Figure 45: Tidal Velocity Variation in Gulf of Khambat over Spring-neap-Spring cycle.**




*Source: IIT Madras*

***(Average velocity = 2 m/s; Prob(V > 2m/s)=0.53; Prob(V > 2.5m/s)=0.37; Prob(V > 3m/s)=0.21)***

The locations identified for tidal stream farm are approximately 60 $km^2$ (on the west) and 35 $km^2$ (on the east) with average water depth of 12.5 m. Hence, it appears that for the present water depth, turbine diameters of up to 7m could be considered with a power rating of 0.25-0.5 MW. With a configuration of 40 turbines per $km^2$, a total of 3,800 turbines could be proposed with a capacity production of 950-1900 MW.

The plant load factor (PLF) is a parameter for defining the actual energy capacity of a plant. This needs extensive hydrodynamic calculations combined with turbine behavior to define the actual plant output to the installed capacity. However, in the absence of detailed numerical simulations, an earlier simulation of a flow field in the Gulf of Khambat is used to define the fraction of time for which the plant can be operated, in the case of TST. A capacity factor (CF) has been defined as the fraction of time that the velocity of water will be more than a threshold value. The typical velocity variation at the gulf is shown in the figure above. Considering the velocity variation, the CF can be defined as a fraction of time for which velocities are above 2m/s. This will be 0.53, considering the turbine operating in both directions of tide (flooding and ebbing).

**Table 19: Capacity Factor Calculation**

| Location | Site conditions | Potential Option | Previous Gross assessment (MW) | Present Gross assessment (MW) | CF |
|---|---|---|---|---|---|
| Khambat | Depth = 12-15m<br>Tidal range = 11m | Barrage (Kalpasar) | 7000 | 7000 | 0.32 |
| | Depth = 12.5m<br>Tidal range = 4m<br>Current = 2.5 m/s | Stream turbine in the gulf | - | 950-1900 (1425 on an average basis) | 0.53 |

*Source: IIT Madras*

The locations identified for tidal stream farms are approximately 60 $km^2$ (on the west) and 35 $km^2$ (on the east) with average water depth of 12.5 m. Hence, it appears that for the present water depth, turbine diameters of up to 7m could be considered with a power rating of 0.25-0.5 MW. With a configuration of 40 turbines per $km^2$, 3,800 turbines could be proposed with production capacity of 950-1900 MW. The following table brings out a comparison of the assessments.

**Table 20: Comparison between Previous and Present Assessment**

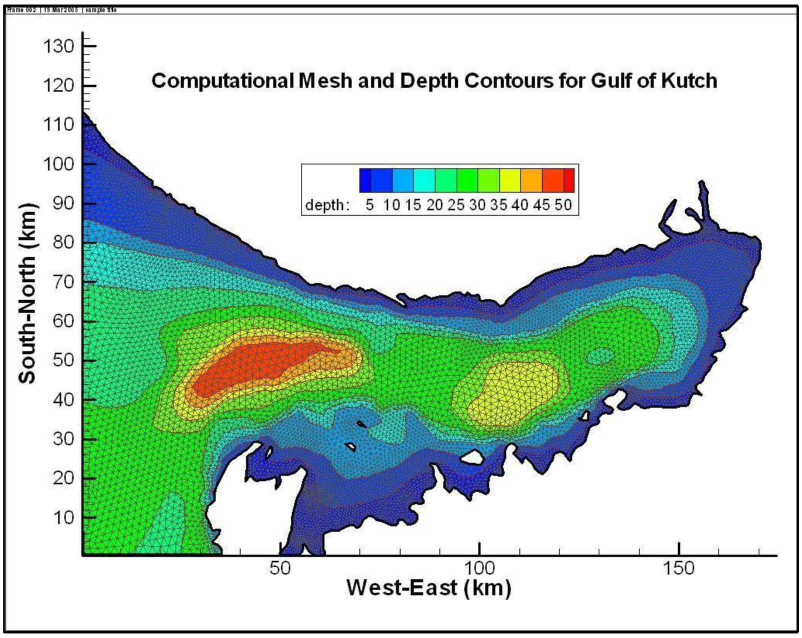
| Location | Site conditions | Potential Option | Previous Gross assessment (MW) | Present Gross assessment (MW) | CF |
|---|---|---|---|---|---|
| Khambat | Depth = 12-15m<br>Tidal range = 11m | Barrage (Kalpasar) | 7000 | 7000 | 0.32 |
| | Depth = 12.5m<br>Tidal range = 4m<br>Current 2.5 m/s | Stream turbine in the Gulf | - | 950-1900 | 0.5-0.6 |

*Source: IIT Madras*

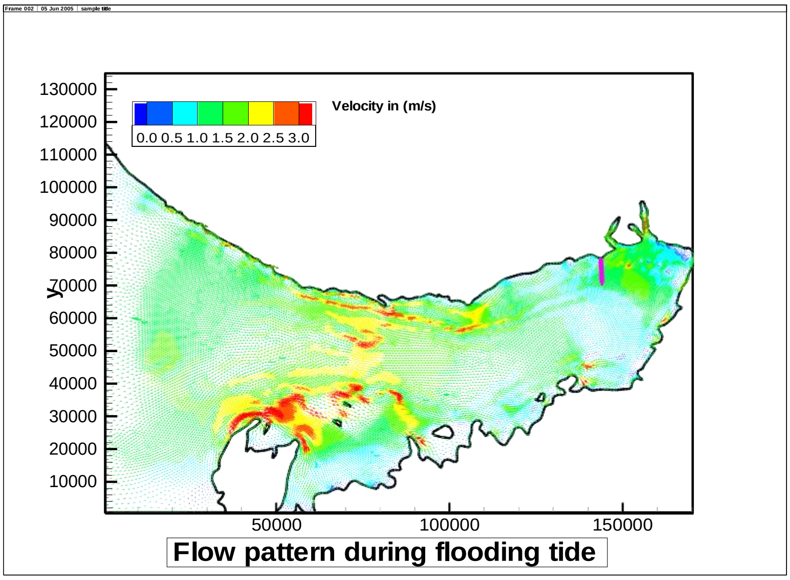
#### 4.1.3.2 Gulf of Kutch

The Gulf of Kutch has features similar to gulf of Kambhat with mean Tidal range of 7m. The bathymetry details and the current patterns in the following figure show the possible regions for tidal stream turbines.

## Figure 46: Proposed Options for Kutch




(a) Bathymetry details of Kutch




(b)Typical velocity patterns in Kutch.

*Source: IIT Madras*

The tide-induced current magnitudes at Kutch are around 3m/s. The average water depth in these regions is around 15-20 m. Using a similar notion to that of Khambat, the amount of energy that could be harnessed from the Gulf Kutch using 0.5 MW tidal stream turbines can be around 2000 MW, taking into account the lower mean velocities in this region. The following table brings out a comparison of the previous and the present assessments.

**Table 21: Comparison between previous and present assessment**

| Location | Site conditions | Potential Option | Previous Gross assessment (MW) | Present Gross assessment (MW) | CF |
|---|---|---|---|---|---|
| **Kutch** | depth = 15-20m<br>tidal range = 3.5m<br>current 3.0 m/s | Stream turbine in the gulf spreading for 100 sq.km | 200<br>(By Atlantis) | 2000 | 0.53 |

### 4.1.3.3 Gulf of Mannar and Palk Bay

The present study considers the channel between the Gulf of Mannar and the Palk bay regions for the development of medium to small-scale tidal power regions in the regions of low tidal range and low tidal streams. The phase lag of six hours makes this region one of the most promising sites for tidal energy extraction as discussed in the previous chapter. The maximum potential energy available will be of about 0.8-1m. This potential difference, with the very large area available on the Palk Bay and the Gulf of Mannar could be used to create a tidal channel with velocities at barrage up to 10m/s. The average water depth available in this region is 6 m. A tidal barrage trapping this tidal range can be constructed for a length of approximately 3 km between the Mandapam and Pamban channels. This arrangement is shown in the map snapshot given below.

**Figure 47: Location of tidal barrage between Mandapam and Pamban channels**


*Source: IIT Madras*

This barrage of 2-3 km length could house up to 1,000 bulb turbines of 1.5m diameter. The power rating of each turbine could be 0.23 MW. Thus, the estimated power that could be harnessed from this location is of the order of 230 MW. However, this estimate could change based on the hydrodynamics study and mechanical design. A pilot study could be considered here followed by a detailed hydraulics, hydrodynamics and EIA study. The following table brings out a comparison of these assessments.

**Table 22: Comparison between Previous and Present Assessments**

| Location | Site conditions | Potential Option | Previous Gross assessment (MW) | Present Gross assessment (MW) | CF |
|---|---|---|---|---|---|
| **Palk Bay - Mannar Channel** | depth = 60m<br>tidal range = 1m, 4 times a day;<br>current 8.0 m/s;<br>25 km$^2$ reservoir | Barrage | - | 230 | 0.4-0.5 |

*Source: IIT Madras*

### Tidal Barrage in Hooghly River – South of Haldia

Another tidal barrage could be proposed on the Hoogly river in the south of Haldia with a width of about 3 km. However, the tide and fresh water flow could reach up to 3m/s as water depth available in this region is 6 m.

**Figure 48: Location of tidal barrage at the mouth of the Hooghly River**


*Source: IIT Madras*

This configuration could accommodate up to 300 x 3 MW turbines. Thus the estimated power that can be harnessed from this location is 900 MW.

**Table 23: Potential Assessment at Hooghly River Location**

| Location | Site conditions | Potential Option | Previous Gross assessment (MW) | Present Gross assessment (MW) | CF |
|---|---|---|---|---|---|
| **Hoogly River** | depth = 6m<br>tidal range = 4-6m;<br>current 3.0 m/s; | Barrage | - | 900 | 0.32 |

| Location | Site conditions | Potential Option | Previous Gross assessment (MW) | Present Gross assessment (MW) | CF |
|---|---|---|---|---|---|
| | 25 km$^2$ reservoir | | | | |

*Source: IIT Madras*

### 4.1.4 Summary of Tidal Power Estimations in India

The power estimates for each site discussed above is summarized in the table below. The gross power estimates and CF are provided as per site conditions.

**Table 24: Summary of Tidal Power Potential Assessment**

| Location | Site conditions | Potential Option | Previous Gross assessment (MW) | Present Gross assessment (MW) | CF |
|---|---|---|---|---|---|
| **Khambat** | depth = 12-15m<br>tidal range = 11m | Barrage (Kalpasar) | 7000 | 7000 | 0.32 |
| | depth = 12.5m<br>tidal range = 4m<br>current 2.5 m/s | Stream turbine in the gulf | - | 1425 | 0.53 |
| **Kutch** | depth = 15-20m<br>tidal range = 3.5m<br>current 3.0 m/s | Stream turbine in the gulf spreading for 100 sq.km | 200<br>(By Atlantis) | 2000 | 0.53 |
| **Palk Bay - Mannar Channel** | depth = 60m<br>tidal range = 1m, 4 times a day;<br>current 1.0 m/s;<br>25 km2 reservoir | Barrage | - | 230 | 0.4-0.5 |
| **Hoogly River** | depth = 6m<br>tidal range = 4-6m;<br>current 3.0 m/s;<br>25 km$^2$ reservoir | Barrage | - | 900 | 0.32 |

*Source: IIT Madras*

The most potential regions for development of tidal energy farms are identified and prioritized. The total estimated potential that is available in these regions is about 11,555 MW, with the lowest limits of capacity factor indicated above. The power that could be produced is estimated as summarized in the following table. Furthermore, there are several sites with large backwaters where the barrage technology could be used.

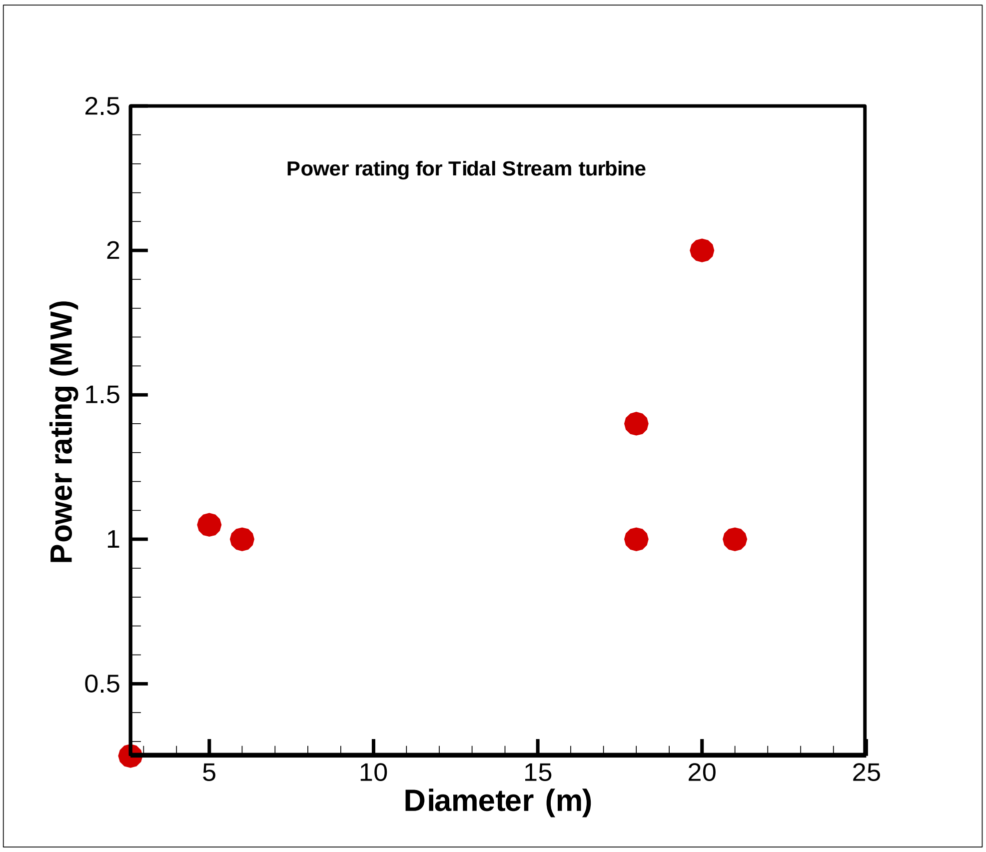
**Table 25: Summary of Potential Tidal Power Estimates**

| Location | Installed capacity (MW) | CF | Power produced (MW) |
|---|---|---|---|
| Khambat | 7000 | 0.32 | 2240 |
| | 950-1900 | 0.53 | 755 |
| Kutch | 2000 | 0.53 | 1060 |
| Palk Bay - Mannar Channel | 230 | 0.4 | 92 |
| Hoogly River | 900 | 0.32 | 288 |
| **Total** | **11555** | | **4435 (MW)** |

*Source: IIT Madras*

However, the tidal stream technology could be adopted in the Khambat and Kutch regions only, after suitable scoping and careful technology demonstration. The technology is not mature enough as brought out below in the rating curve based on available data. No clear trend is emerging as far as the selection of turbines is concerned. These points at several uncertainties in design and performance of TSTs which may act as a major stumbling block in implementing this technology in India, as against the barrage technology which is mature enough.

**Figure 49: Rating curve of turbines**




*Source: IIT Madras*

In the backdrop of the above discussions, there is an urgent need to:

- Create a pilot project using the barrage and stream concepts. Such studies should consider hybridization of the PTO arrangement with the option of combined wind / solar arrangements.
- Understand environmental and other issues pertaining to this energy form.
- Create a clear roadmap for the promotion of tidal energy and individual and hybrid technologies.

The state wise potential is mentioned below.

**Figure 50 : State-wise potential of tidal energy**

| State | Tidal Range (m) | Technology | Diameter (m) of a turbine | Capacity of a turbine (MW) | no of turbines | Tidal power potential (MW) |
|---|---|---|---|---|---|---|
| Gujarat (Gulf of Kutch) | 4-9 m | Tidal Stream Turbine | 7 | 0.5 | 4000 | 2000 |
| Gujarat (Gulf of Khambat) | 5-11 m | Tidal Barrage/ Tidal stream turbine | 7 | 0.25-0.5 | 3800 | 950-1900 MW using TST + 7000 MW using Barrage |
| Maharashtra | 2-4 m | Tidal Barrage | 4 | 2 | 100 | 200 |
| Karnataka | 1-1.5 m | Tidal Barrage | 2 | 0.5 | 200 | 100 |
| Kerala | 1-1.5 m | Tidal Barrage | 2 | 0.5 | 200 | 100 |
| Tamil Nadu (Gulf of Mannar and Palk Bay | 0.8-1 m | Tidal Barrage | 1.5 | 0.23 | 1000 | 230 |
| Andhra Pradesh | 1-2 m | Tidal Barrage | 3 | 0.75 | 133 | 100 |
| West Bengal (Sunderbans) | 4-6 m | Tidal Barrage | 5 | 3 | 300 | 900 |
| Orissa | 2-4 m | Tidal Barrage | 4 | 2 | 200 | 400 |

*Source: IIT-Madras & CRIS analysis*

## 4.2 Wave Energy

In order to explore the wave energy potential along the Indian coast in detail, 10-year simulation wave data has been utilized. The third-generation wind-wave model WAM has been employed to generate wave data of ten years from 1993 to 2002 in the Indian Ocean [Sannasiraj, 2007]. The hindcast wind of QUICKSCAT with a resolution of $0.25^{o}$ x $0.25^{o}$ has been utilized. The offshore wave climate off the Indian coasts has been extracted at salient points. The distributions of wave power potential along the Indian coastline are projected in the following table and figure respectively.

Table 26: Distributions of Wave Power Potential along Indian Coastline

| Sr. No | Places | State | Lat | Lon | $H_{max}$ (m) | $H_{av}$ (m) | Hs (m) | $T_{mean}$ (s) | $q_{mean}$ ($^{o}$) | Powerk w/m | Wave Lt. (m) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Madhi | Gujarat | 22.00 | 69.00 | 3.57 | 1.25 | 1.98 | 7.21 | 232 | 13.93 | 81.10 |
| 2 | Gojines | Gujarat | 22.00 | 69.13 | 1.35 | 0.47 | 0.75 | 3.5 | 233 | 0.97 | 19.11 |
| 3 | Porbandar | Gujarat | 21.50 | 69.50 | 3.40 | 1.19 | 1.89 | 7.33 | 228 | 12.83 | 83.82 |
| 4 | Mangrol | Gujarat | 21.00 | 70.00 | 3.46 | 1.21 | 1.92 | 6.89 | 242 | 12.47 | 74.06 |
| 5 | Khambhaliya | Gujarat | 21.01 | 70.12 | 1.35 | 0.47 | 0.75 | 3.5 | 233 | 0.97 | 19.11 |
| 6 | Jafrabed | Gujarat | 20.42 | 71.50 | 1.35 | 0.47 | 0.75 | 3.5 | 248 | 0.97 | 19.11 |
| 7 | Narpad | Gujarat | 20.00 | 71.51 | 1.35 | 0.47 | 0.75 | 3.5 | 248 | 0.97 | 19.11 |
| 8 | Haveli | Gujarat | 20.00 | 72.50 | 2.43 | 0.85 | 1.35 | 5.73 | 232 | 5.12 | 51.22 |
| 9 | Virar | Gujarat | 19.50 | 72.50 | 2.91 | 1.02 | 1.62 | 5.97 | 243 | 7.68 | 55.60 |
| 13 | Bandra | Mumbai | 19.00 | 72.57 | 1.35 | 0.47 | 0.75 | 3.5 | 248 | 0.97 | 19.11 |
| 10 | Pune | Maharastra | 18.50 | 72.50 | 3.51 | 1.23 | 1.95 | 6.99 | 252 | 13.07 | 76.22 |
| 11 | Guhagar | Maharastra | 17.50 | 73.00 | 3.51 | 1.23 | 1.95 | 7.68 | 254 | 14.36 | 92.01 |
| 12 | Ratnagiri | Maharastra | 17.00 | 73.00 | 3.89 | 1.36 | 2.16 | 7.61 | 258 | 17.40 | 90.34 |
| 14 | Shrivardhan | Maharastra | 18.00 | 72.84 | 1.35 | 0.47 | 0.75 | 3.5 | 248 | 0.97 | 19.11 |
| 15 | Jakimiraya | Maharastra | 17.00 | 73.18 | 1.35 | 0.47 | 0.75 | 3.5 | 263 | 0.97 | 19.11 |
| 16 | Rajapur | Maharastra | 16.50 | 73.00 | 4.11 | 1.44 | 2.29 | 7.78 | 259 | 19.94 | 94.42 |
| 17 | Kudal | Maharastra | 16.00 | 73.00 | 4.26 | 1.49 | 2.37 | 8 | 260 | 21.95 | 99.84 |
| 18 | Tarkarli | Maharastra | 16.00 | 73.39 | 1.35 | 0.47 | 0.75 | 4.5 | 263 | 1.24 | 31.59 |
| 19 | Panaji | Goa | 15.50 | 73.50 | 3.91 | 1.37 | 2.17 | 8.24 | 251 | 19.12 | 105.92 |
| 20 | Agonda | Goa | 15.00 | 73.87 | 1.35 | 0.47 | 0.75 | 4.5 | 263 | 1.24 | 31.59 |

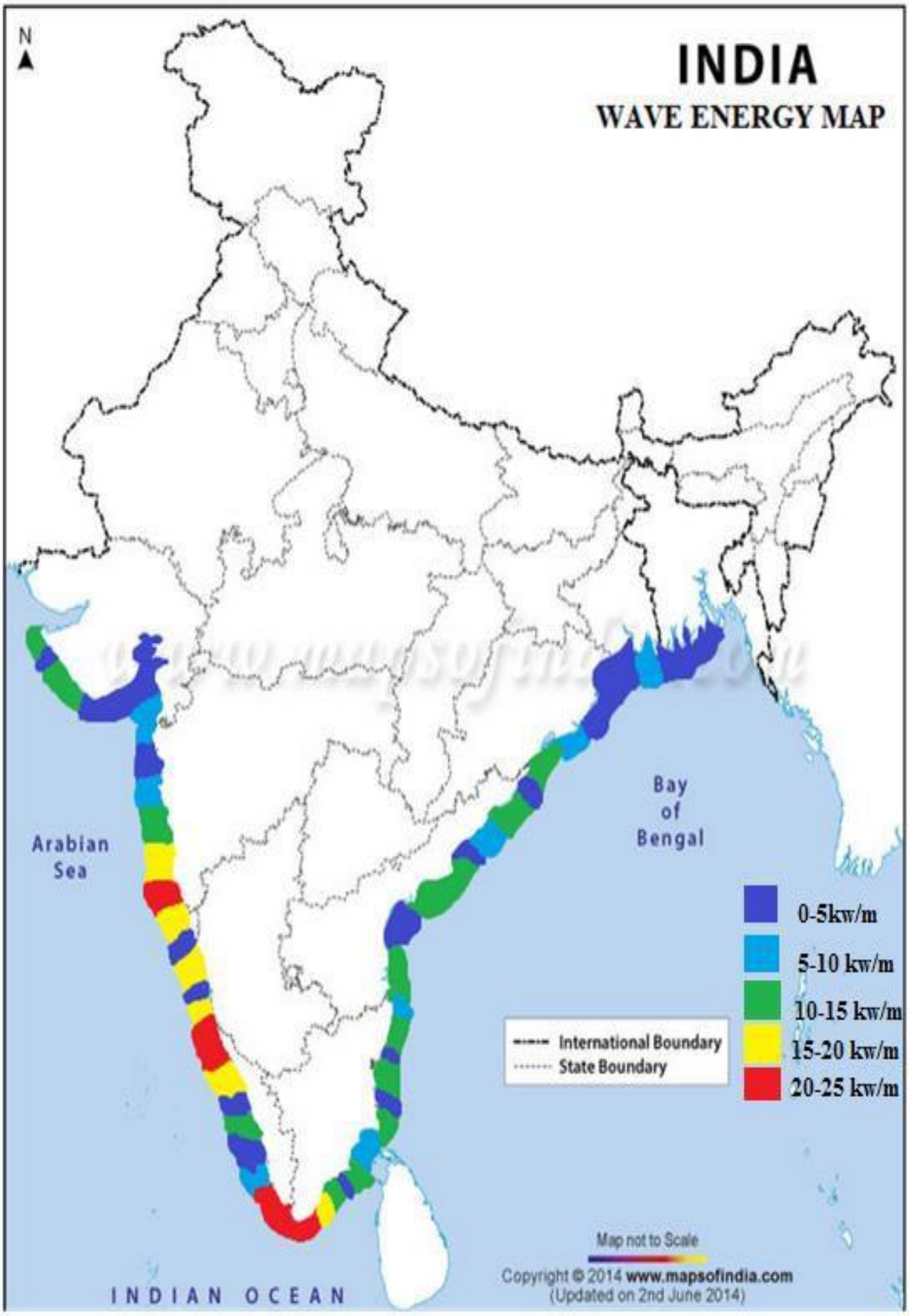
| Sr. No | Places | State | Lat | Lon | $H_{max}$ (m) | $H_{av}$ (m) | Hs (m) | $T_{mean}$ (s) | $q_{mean}$ (°) | Powerk w/m | Wave Lt. (m) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 21 | Gokarna | Karnataka | 14.50 | 74.00 | 3.89 | 1.36 | 2.16 | 8.38 | 247 | 19.16 | 109.6 |
| 22 | Tenginagundi | Karnataka | 14.00 | 74.39 | 1.35 | 0.47 | 0.75 | 4.5 | 263 | 1.24 | 31.59 |
| 23 | Barkur | Karnataka | 13.50 | 74.50 | 3.60 | 1.26 | 2.00 | 8.33 | 249 | 16.35 | 108.3 |
| 24 | Surathkal | Karnataka | 13.00 | 74.50 | 4.03 | 1.41 | 2.24 | 8.32 | 253 | 20.45 | 108.0 |
| 25 | Sasihithlu | Karnataka | 13.00 | 74.68 | 1.35 | 0.47 | 0.75 | 4.5 | 263 | 1.24 | 31.59 |
| 26 | Kasaragod | Kerala | 12.50 | 74.50 | 4.26 | 1.49 | 2.37 | 8.43 | 253 | 23.13 | 110.9 |
| 27 | Taliparambha | Kerala | 12.00 | 75.00 | 3.86 | 1.35 | 2.14 | 8.49 | 247 | 19.13 | 112.4 |
| 28 | Ettikulam | Kerala | 12.00 | 75.10 | 1.35 | 0.47 | 0.75 | 4.5 | 263 | 1.24 | 31.59 |
| 29 | Payyoli | Kerala | 11.50 | 75.50 | 3.34 | 1.17 | 1.86 | 8.27 | 246 | 13.99 | 106.7 |
| 30 | Parapanangadi | Kerala | 11.00 | 75.73 | 1.35 | 0.47 | 0.75 | 4.5 | 263 | 1.24 | 31.59 |
| 31 | Calicut | Kerala | 11.00 | 75.50 | 4.06 | 1.42 | 2.25 | 8.52 | 247 | 21.24 | 113.2 |
| 32 | Thrissur | Kerala | 10.50 | 76.00 | 0.74 | 0.26 | 0.41 | 9.26 | 241 | 0.77 | 133.8 |
| 33 | Vypin | Kerala | 10.00 | 76.07 | 1.35 | 0.47 | 0.75 | 4.5 | 278 | 1.24 | 31.59 |
| 34 | Cochin | Kerala | 10.00 | 76.00 | 3.94 | 1.38 | 2.19 | 8.68 | 239 | 20.43 | 117.5 |
| 35 | Allepey | Kerala | 9.50 | 76.00 | 4.14 | 1.45 | 2.30 | 8.79 | 242 | 22.84 | 120.5 |
| 36 | Thurayilkunnu | Kerala | 9.00 | 76.42 | 1.35 | 0.47 | 0.75 | 5.5 | 263 | 1.52 | 47.19 |
| 37 | Kollam | Kerala | 9.00 | 76.50 | 2.86 | 1.00 | 1.59 | 8.49 | 233 | 10.49 | 112.4 |
| 38 | Trivandrum | Kerala | 8.50 | 76.50 | 4.31 | 1.51 | 2.40 | 8.9 | 230 | 25.08 | 123.6 |
| 39 | Nagerkoil | Tamil Nadu | 8.00 | 77.00 | 4.63 | 1.62 | 2.57 | 8.73 | 207 | 28.32 | 118.9 |
| 40 | Kanniyakumari | Tamil Nadu | 8.00 | 77.50 | 4.31 | 1.51 | 2.40 | 8.3 | 197 | 23.39 | 107.5 |
| 41 | Koodankulam | Tamil Nadu | 8.00 | 78.00 | 4.74 | 1.66 | 2.63 | 8.38 | 191 | 28.54 | 109.6 |

| Sr. No | Places | State | Lat | Lon | $H_{max}$ (m) | $H_{av}$ (m) | Hs (m) | $T_{mean}$ (s) | $q_{mean}$ (°) | Powerk w/m | Wave Lt. (m) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 42 | Tiruchendur | Tamil Nadu | 8.50 | 78.50 | 3.89 | 1.36 | 2.16 | 8.05 | 164 | 18.40 | 101.1 |
| 43 | Tuticorin | Tamil Nadu | 9.00 | 78.50 | 3.26 | 1.14 | 1.81 | 7.91 | 167 | 12.71 | 97.61 |
| 44 | Devipatnam | Tamil Nadu | 9.50 | 79.00 | 2.34 | 0.82 | 1.30 | 6.69 | 168 | 5.56 | 69.82 |
| 45 | Keraikudi | Tamil Nadu | 10.00 | 79.50 | 0.46 | 0.16 | 0.25 | 8.5 | 161 | 0.27 | 112.7 |
| 46 | Velakkani | Tamil Nadu | 10.50 | 80.00 | 2.91 | 1.02 | 1.62 | 6.79 | 133 | 8.73 | 71.92 |
| 47 | Kottuchery | Tamil Nadu | 11.00 | 79.94 | 1.35 | 0.47 | 0.75 | 3.5 | 158 | 0.97 | 19.11 |
| 48 | Karaikkal | Tamil Nadu | 11.00 | 80.00 | 3.03 | 1.06 | 1.68 | 7.16 | 131 | 9.94 | 79.97 |
| 49 | Pitchavaram | Tamil Nadu | 11.50 | 80.00 | 3.23 | 1.13 | 1.79 | 7.5 | 131 | 11.84 | 87.75 |
| 50 | Puducherry | Tamil Nadu | 12.00 | 80.00 | 3.00 | 1.05 | 1.67 | 7.77 | 135 | 10.59 | 94.18 |
| 51 | Kalpakkam | Tamil Nadu | 12.50 | 80.50 | 3.54 | 1.24 | 1.97 | 7.83 | 134 | 14.88 | 95.64 |
| 52 | Chennai | Tamil Nadu | 13.00 | 80.50 | 3.37 | 1.18 | 1.87 | 7.71 | 136 | 13.27 | 92.73 |
| 53 | Pulicat | Andhra Pradesh | 13.50 | 80.50 | 3.40 | 1.19 | 1.89 | 7.88 | 138 | 13.79 | 96.87 |
| 54 | Pambali | Andhra Pradesh | 14.00 | 80.33 | 1.35 | 0.47 | 0.75 | 3.5 | 128 | 0.97 | 19.11 |
| 55 | Durgarajupatnam | Andhra Pradesh | 14.00 | 80.50 | 3.40 | 1.19 | 1.89 | 7.92 | 140 | 13.86 | 97.85 |
| 56 | Krishnapatnam | Andhra Pradesh | 14.50 | 80.50 | 3.43 | 1.20 | 1.90 | 7.95 | 144 | 14.15 | 98.60 |
| 57 | Mulampeta | Andhra Pradesh | 15.00 | 80.19 | 1.35 | 0.47 | 0.75 | 3.5 | 143 | 0.97 | 19.11 |
| 58 | Chakicherla | Andhra Pradesh | 15.00 | 80.00 | 1.83 | 0.64 | 1.02 | 6.7 | 159 | 3.39 | 70.03 |
| 59 | Ammanabrole | Andhra Pradesh | 15.50 | 80.50 | 2.31 | 0.81 | 1.29 | 7.5 | 156 | 6.08 | 87.75 |
| 60 | Palakayatippa | Andhra Pradesh | 16.00 | 81.32 | 1.35 | 0.47 | 0.75 | 3.5 | 158 | 0.97 | 19.11 |
| 61 | Machilipattinam | Andhra Pradesh | 16.00 | 81.50 | 3.29 | 1.15 | 1.83 | 8.08 | 155 | 13.21 | 101.85 |
| 62 | Yanam | Andhra Pradesh | 16.50 | 82.50 | 3.66 | 1.28 | 2.03 | 8.13 | 159 | 16.47 | 103.1 |

| Sr. No | Places | State | Lat | Lon | $H_{max}$ (m) | $H_{av}$ (m) | Hs (m) | $T_{mean}$ (s) | $q_{mean}$ (°) | Powerk w/m | Wave Lt. (m) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 63 | Chintapalle | Andhra Pradesh | 17.00 | 82.43 | 0.45 | 0.16 | 0.25 | 3.5 | 143 | 0.11 | 19.11 |
| 64 | Kakinada | Andhra Pradesh | 17.00 | 82.50 | 3.26 | 1.14 | 1.81 | 8.08 | 160 | 12.98 | 101.9 |
| 65 | Pudimadaka | Andhra Pradesh | 17.50 | 83.00 | 2.86 | 1.00 | 1.59 | 7.68 | 165 | 9.49 | 92.01 |
| 66 | Konada | Andhra Pradesh | 18.00 | 83.50 | 2.46 | 0.86 | 1.37 | 7.55 | 169 | 6.90 | 88.92 |
| 67 | Penumatti | Andhra Pradesh | 18.00 | 83.76 | 1.35 | 0.47 | 0.75 | 4.5 | 173 | 1.24 | 31.59 |
| 68 | Naupada | Andhra Pradesh | 18.50 | 84.50 | 3.51 | 1.23 | 1.95 | 7.92 | 169 | 14.81 | 97.85 |
| 69 | Pukkalapalyam | Andhra Pradesh | 18.98 | 1.35 | 1.35 | 0.47 | 0.75 | 4.5 | 188 | 1.24 | 31.59 |
| 70 | Kaviti | Andhra Pradesh | 19.00 | 85.00 | 3.54 | 1.24 | 1.97 | 7.87 | 171 | 14.96 | 96.62 |
| 71 | Malud | Orissa | 19.50 | 85.50 | 3.40 | 1.19 | 1.89 | 7.77 | 173 | 13.60 | 94.18 |
| 72 | Nuliasahi | Orissa | 20.00 | 86.50 | 2.91 | 1.02 | 1.62 | 7.3 | 174 | 9.39 | 83.13 |
| 73 | Mankadakhia | Orissa | 20.00 | 86.53 | 1.35 | 0.47 | 0.75 | 3.5 | 188 | 0.97 | 19.11 |
| 74 | Kendrapara | Orissa | 20.50 | 87.00 | 2.37 | 0.83 | 1.32 | 7.14 | 173 | 6.08 | 79.53 |
| 75 | Bideipur | Orissa | 21.00 | 87.00 | 1.49 | 0.52 | 0.83 | 5.62 | 175 | 1.88 | 49.27 |
| 76 | Chandipur | Orissa | 21.00 | 87.41 | 1.35 | 0.47 | 0.75 | 3.5 | 188 | 0.97 | 19.11 |
| 77 | Dantan | West Bengal | 21.50 | 87.50 | 1.03 | 0.36 | 0.57 | 6.95 | 181 | 1.11 | 75.35 |
| 78 | Nandigram | West Bengal | 22.00 | 88.00 | 1.23 | 0.43 | 0.68 | 4.36 | 196 | 1.00 | 29.65 |
| 79 | Bakhkhali | West Bengal | 21.50 | 88.50 | 2.31 | 0.81 | 1.29 | 6.38 | 177 | 5.17 | 63.50 |
| 80 | Sundarban | West Bengal | 22.00 | 89.00 | 1.94 | 0.68 | 1.08 | 5.78 | 186 | 3.30 | 52.12 |

*Source: IIT Madras*

**Figure 51: Wave Energy Map for India**




*Source: IIT Madras*

From the map, it can be seen that the contour of 10-15 kW/m is distributed almost evenly along the western and eastern coasts. Further, the wave contours of 15-20 kW/m are observed along the west coast, off viz., Maharashtra, Goa, Karnataka and Kerala. This presence of higher power along the west coast could probably be due to the strong waves during the south-west monsoon. Maximum wave power is obtained at the southern tip of the Indian peninsula (Kanyakumari, Nagercoil district, Koodankulam) which could be due to the effect of refraction and the presence of strong winds prevailing in the region.

The distribution of wave power in a finite range and the length of coastline over which it is spread are grouped and presented in the following table.

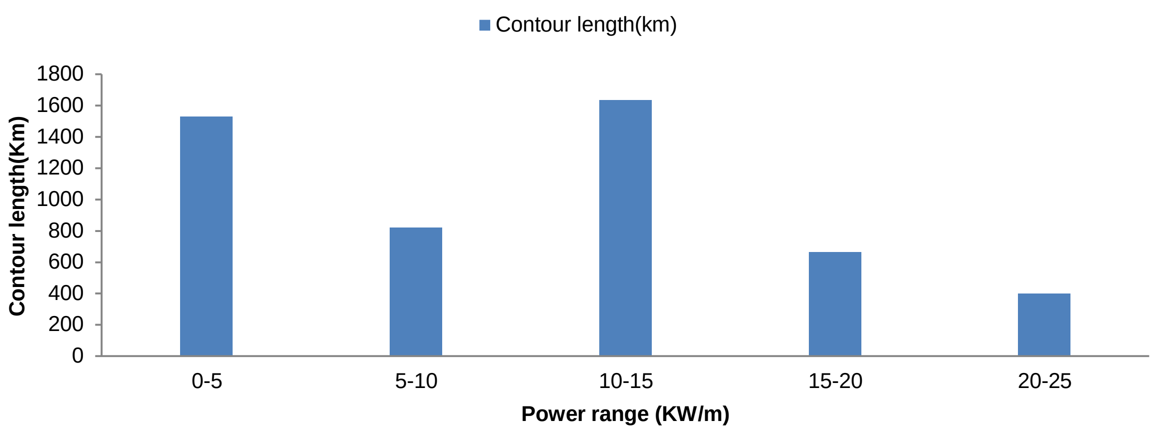
**Table 27: Wave Power Contours**

| Contour power level(kW/m) | Contour length(km) | Total power flux crossing contour(GW) |
|---|---|---|
| **0-5** | 1530 | 3.825 |
| **5-10** | 822 | 6.165 |
| **10-15** | 1634 | 20.425 |
| **15-20** | 665 | 11.64 |
| **20-25** | 400 | 9 |

*Source: IIT Madras*

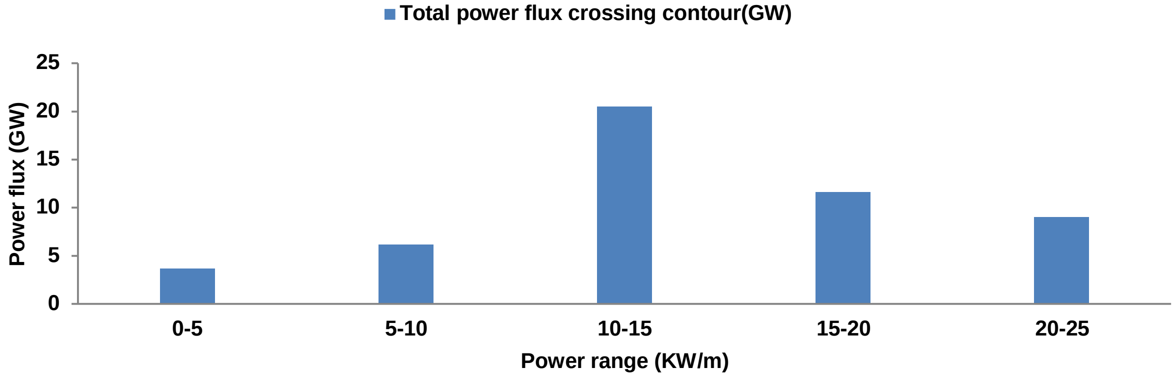
The distribution along the length of the coast and the total power available in each power contour is also shown by the following graphs.

**Figure 52: Distribution of wave energy along different latitudes of Indian Coast**




*Source: IIT Madras*

**Figure 53: Total power flux available along different latitudes of Indian coast**




*Source: IIT Madras*

The wave energy concentration along the coastal stretch of different maritime states is projected in the table mentioned below. It is to be noted that the revised estimate shows that the total power available along the coast line is about 50 GW. However, considering wave power above 10kW/m, if efficiently harvested, the total power available would be 41 GW which is matching with the wave estimate in eighties of 40 GW.

It should further be noted that the entire 41GW could not be harvested due to many other physical morph dynamic factors and site conditions such as water depth. A realistic estimate at each site can be made based on detailed surveys along a particular coastal stretch.

**Table 28: Wave power contours along different maritime states**

| State | Contour length(km) | Total power flux crossing contour(GW) | Contour power level(kW/m) |
|---|---|---|---|
| Gujarat | 0-5 | 465 | 1.2 |
| | 5-10 | 110 | 0.8 |
| | 10-15 | 325 | 4.1 |
| Maharashtra | 0-5 | 90 | 0.2 |
| | 5-10 | 115 | 0.9 |
| | 10-15 | 120 | 1.5 |
| | 15-20 | 210 | 3.7 |
| | 20-25 | 130 | 2.9 |
| Karnataka | 0-5 | 130 | 0.3 |
| | 15-20 | 215 | 3.8 |
| | 20-25 | 95 | 2.2 |
| Kerala | 0-5 | 130 | 0.3 |
| | 5-10 | 60 | 0.5 |
| | 10-15 | 65 | 0.8 |
| | 15-20 | 125 | 2.2 |
| | 20-25 | 85 | 1.9 |

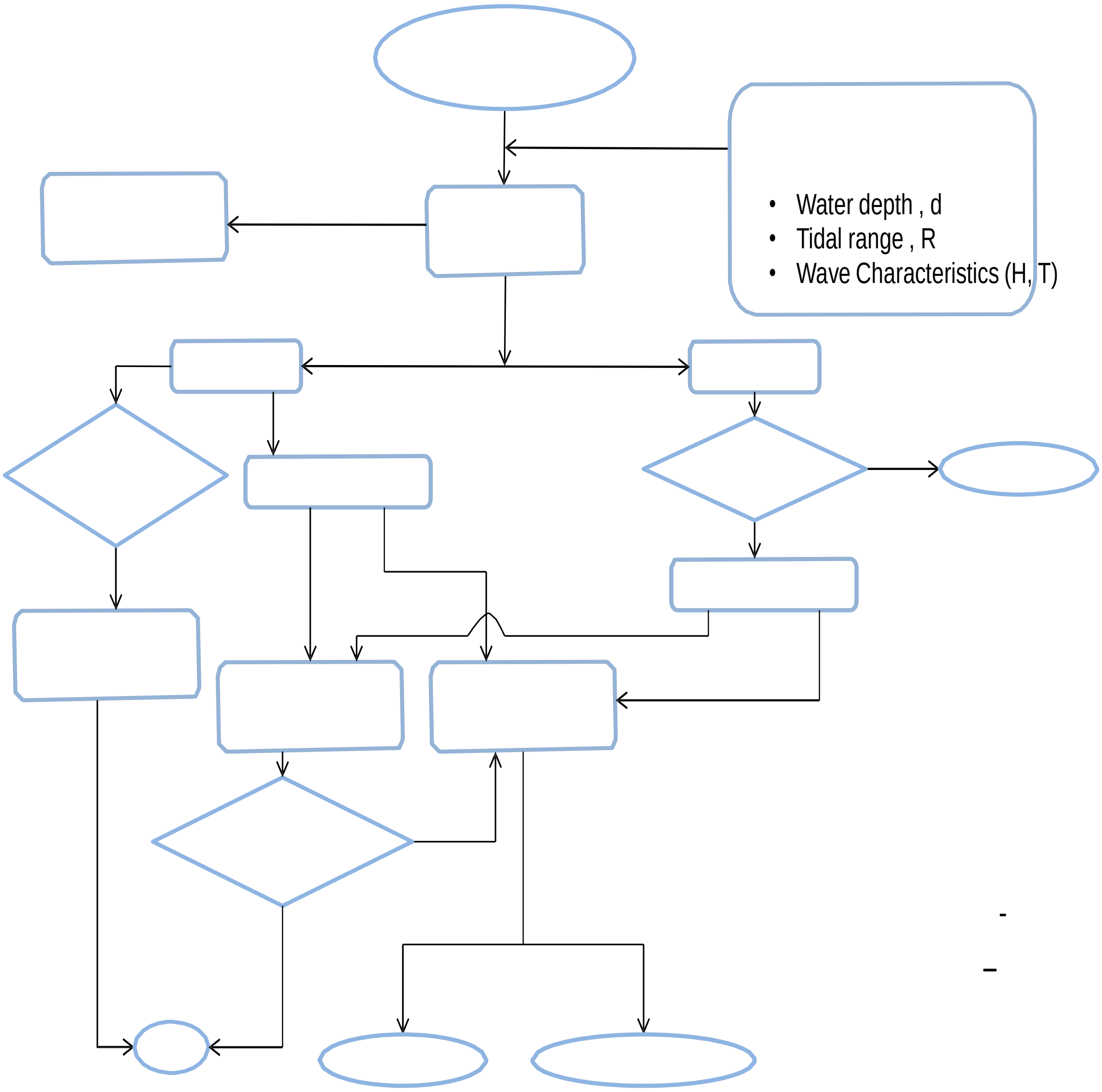
| State | Contour length(km) | Total power flux crossing contour(GW) | Contour power level(kW/m) |
|---|---|---|---|
| **Tamil Nadu** | 0-5 | 75 | 0.1 |
| | 5-10 | 110 | 0.8 |
| | 10-15 | 529 | 6.6 |
| | 15-20 | 115 | 2.0 |
| | 20-25 | 90 | 2 |
| **Andhra Pradesh** | 0-5 | 150 | 0.4 |
| | 5-10 | 85 | 0.6 |
| | 10-15 | 550 | 6.9 |
| **Orissa** | 0-5 | 235 | 0.6 |
| | 5-10 | 160 | 1.2 |
| | 10-15 | 45 | 0.6 |
| **West Bengal** | 0-5 | 255 | 0.6 |
| | 5-10 | 182 | 1.4 |

*Source: IIT Madras*

### 4.2.1 Feasible Sites for Wave Energy in India

For final site selection, various other parameters, such as near shore slope, daily wave statistics, and availability of land, local demand and grid connectivity need to be considered. The flow chart below presents the selection strategy for the wave energy device.

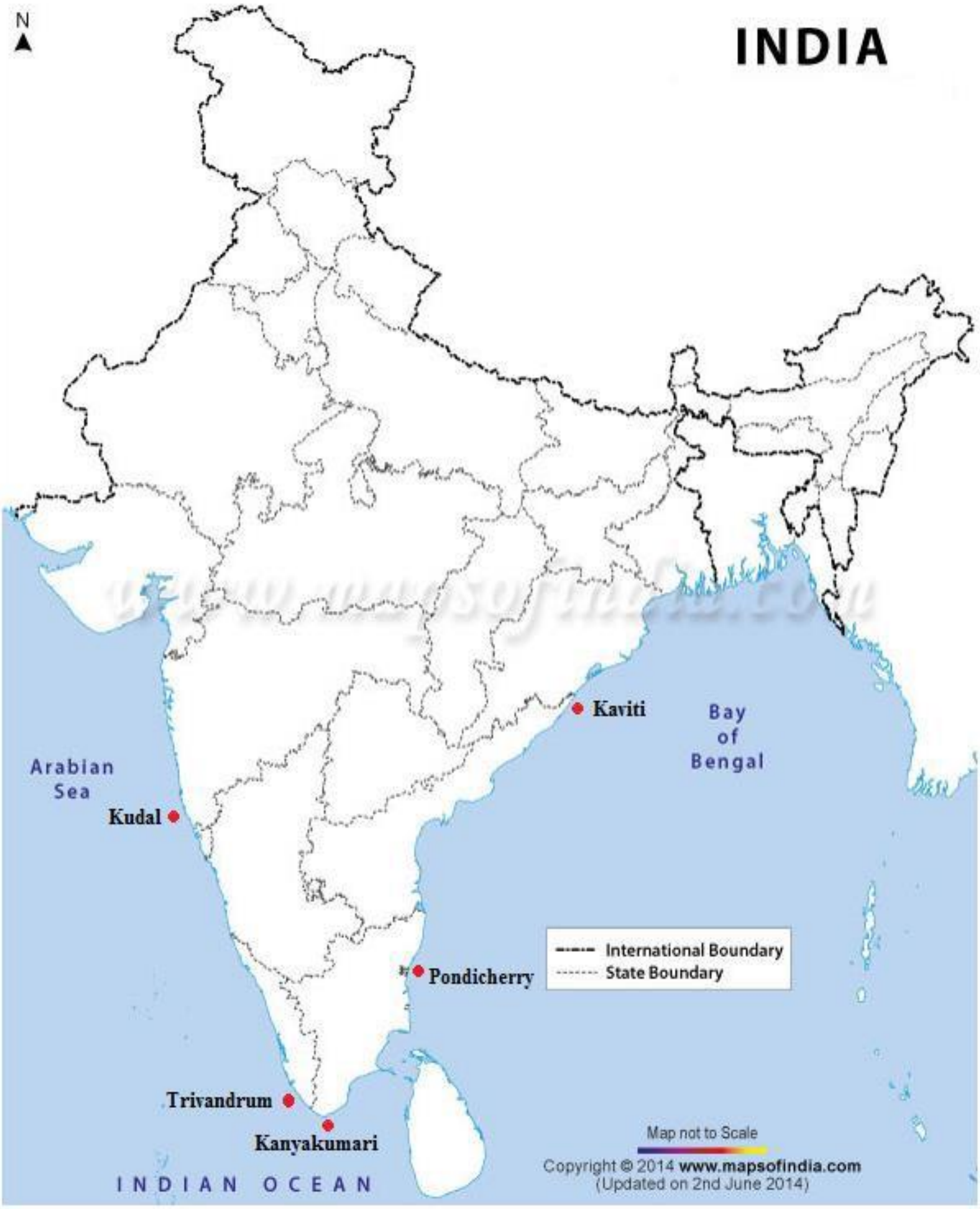
**Figure 54: Selection Strategy for Wave Energy Device Deployment**




*Source: IIT Madras*

Based on the statistics of wave characteristics discussed in the last chapter, five potential sites suitable for the deployment of wave energy devices have been chosen. It is to be noted that the selection is only based on the magnitude of wave energy and its distribution along the entire Indian coast. The chosen coastal sites for deployment of wave energy devices has been highlighted in the map of India below and its comparison with earlier estimates is presented in the subsequent table.

Figure 55: Potential Coastal Locations for Wave Energy Harvesting




*Source: IIT Madras*

**Table 29: Comparison between Previous and Current Potential Assessment**

| S.No | Location | States/UT | Place | Wave power estimate in 1982 (kW/m) | Current assessment of wave power (KW/m) |
|---|---|---|---|---|---|
| 1 | 15-25° N and coast-70° E(off Bombay) | Maharastra | Kudal | 46.98 | 21.95 |

| S.No | Location | States/UT | Place | Wave power estimate in 1982 (kW/m) | Current assessment of wave power (KW/m) |
|---|---|---|---|---|---|
| 2 | 5-10° N and coast-75-80° E(off cape comorin) | Kerala | Trivandrum | 19.52 | 25.08 |
| 3 | 5-10° N and coast-75-80° E(off cape comorin) | Tamil Nadu | Kanyakumari | 19.52 | 23.39 |
| 4 | 10-15° N and coast-85° E(off Madras) | Tamil nadu | Puducherry | 16.62 | 10.59 |
| 5 | 15-20° N and coast-85 E(off Visakhapatnam) | Andhra Pradesh | Kaviti | 33.65 | 14.96 |

*Source: IIT Madras*

The conditions of the proposed sites with estimated power are summarized in the table below.

**Table 30: Conditions for Proposed Sites**

| Sr. No | State/UT | Place | Lat | Long | Water depth(m) | $H_s$(m) | $T_s$(s) | Power (KW/m) |
|---|---|---|---|---|---|---|---|---|
| 1 | Maharastra | Kudal | 15°55'N | 73°32'E | 11-12 | 2.37 | 8 | 21.95 |
| 2 | Kerala | Trivandrum | 8°28'N | 76°54'E | 15-20 | 2.4 | 8.9 | 25.08 |
| 3 | Tamil Nadu | Kanniyakumari | 8°4'N | 77°32'E | 12-13 | 2.4 | 8.3 | 23.39 |
| 4 | Tamil Nadu | Puducherry | 11°54'N | 79°50'E | 5-8 | 1.67 | 7.77 | 10.59 |
| 5 | AndhraPradesh | Kaviti | 19°00'N | 84°43'E | 10-14 | 1.97 | 7.87 | 14.96 |

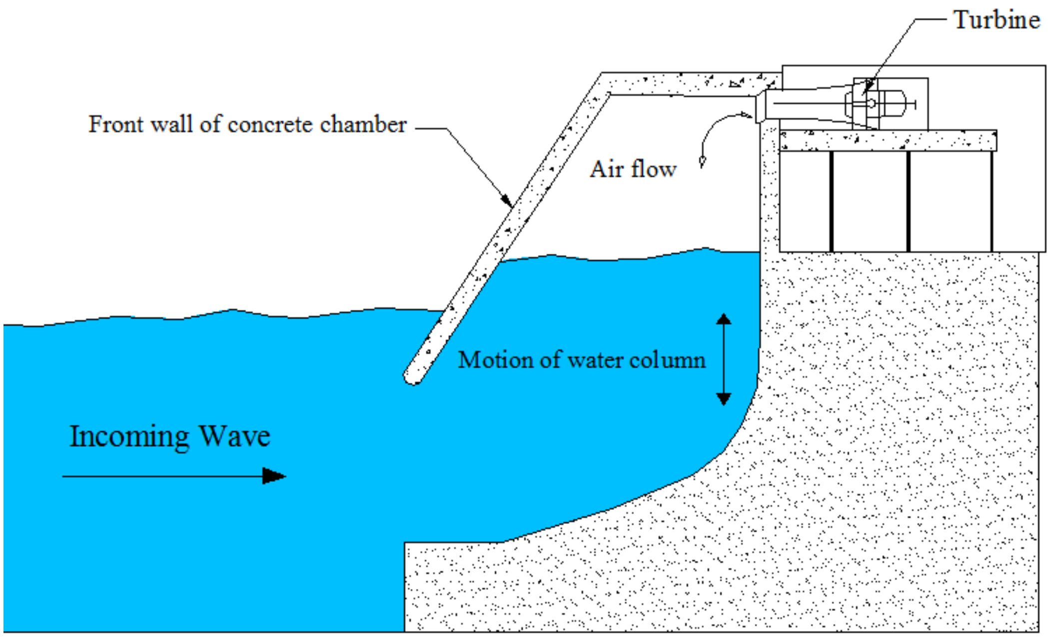
*Source: IIT Madras*

#### 4.2.1.1 Coast of Maharashtra (Kudal)

Wave power potential is found to be higher along the west coast, in particular, off Maharashtra. The total power potential along the 720 km stretch of the Maharashtra coast is approximately 9,200 MW for wave energy plants if the entire stretch is been installed with energy extraction devices. However, it is not feasible and a typical coastal site like Kudal has been taken as a representative site. The main idea of presenting only five coastal sites is to provide the possibility of implementation of the device selection strategy. The number of units in each site might vary in a wide range depending on economical and physical criteria.

OWC is the simplest and most adaptable device along the coastal structure. The sketch of OWC is shown in the figure below. The OWC system consists of a chamber in the sea which is exposed to wave action through the entrance at the bottom. As water rises and falls around and inside OWC, air is displaced by the water in a collecting chamber and pushed back and front to rotate the turbine, coupled with a generator to produce electricity. This technology was adopted at Vizhijam along the Kerala coast by NIOT, Chennai with design power generation of 150 kW.

**Figure 56: Sketch showing various components of OWC**




*Source: IIT Madras*

Basic OWC components are collecting chamber, power take-off (PTO) and wells turbine. The amount of energy which can be converted into useful energy depends strongly on the design of the chamber. The PTO system converts pneumatic power into the desired energy and is very important for the efficiency of OWC. Turbines used in OWC are bidirectional. The wells turbine is thus designed with symmetrical aero foil. The airfoils spin in the same direction regardless of the direction of air flow.

The identified sites in Maharashtra to install OWC are Ratnagiri and Kudal. These sites possess large wave potential throughout the year and in particular during June to August.

#### 4.2.1.2 Coast of Kerala (Trivandrum)

Vizhinjam OWC was a successful installation during the pilot stage of device development and has been a successful demonstration plant. But slowly it went out of use and was decommissioned in 2011. The problems that were faced at Vizhinjam design can be reviewed and improved to set up an OWC with appropriate features at these places in Kerala, which has almost similar features.

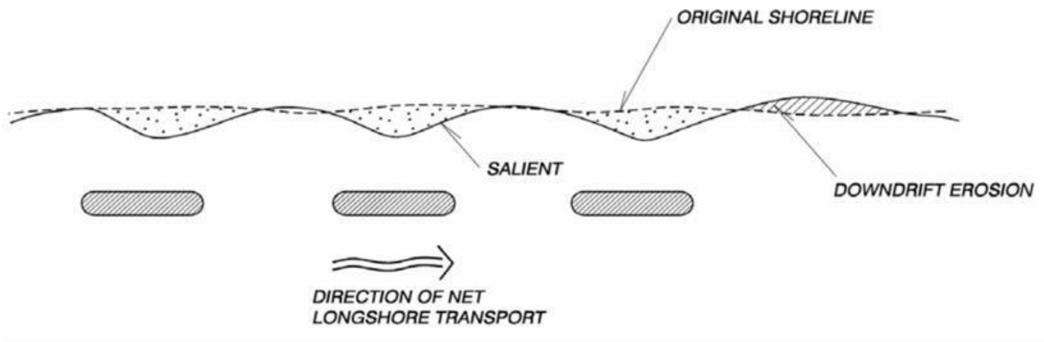
#### 4.2.1.3 Coast of Tamil Nadu (Kanyakumari)

Average wind speed is approximately 9 m/s and power obtained from the wind farm in Kanyakumari is about 220 MW. This region has the highest wave power among the locations chosen, with an average wave power of 23kW/m. This is one among best available wave power in the country. Hence, the best possible device that could be used at Kanyakumari would be a hybrid wind and wave energy converter similar to Poseidon‟s concept of floating power plant. Here, floating devices are recommended to avoid shore-connected systems. The figure is mentioned below for floating devices and typical sketch of off-shore break-water systems.

**Figure 57 : Floating Power Plant**

*Source: IIT Madras and www.floatingpowerplant.com*

**Figure 58 : Sketch of off-shore protection system**




$$W \approx \frac{\lambda}{2\pi} \sim \mathrm{O}(10 \text{ to } 15\text{m}) \quad \textit{capture width}$$

*Source: IIT Madras*

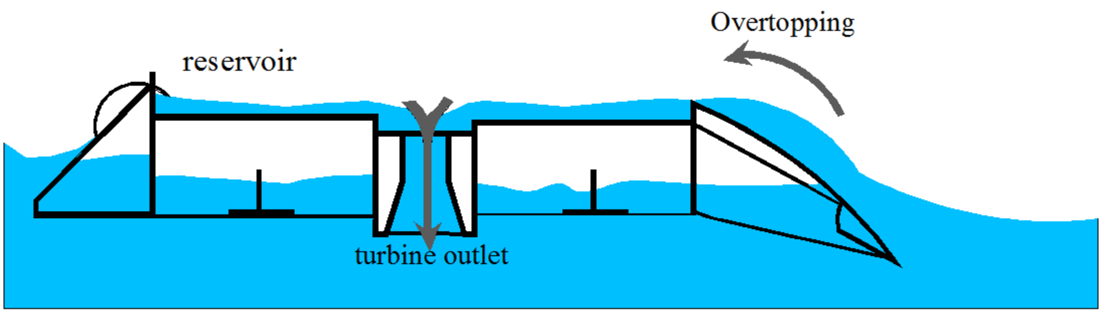
#### 4.2.1.4 Coast of Puducherry

The average wave power that can be harvested in Puducherry is 10.5 kW/m coastlines. Due to the limited length of the coastline for this Union Territory and the high threat of erosion all along the coastline of Puducherry, it is recommended to integrate the coastal defense structures with the wave energy device. This is possible with the deployment of OWC. If one protects the entire coastline of nearly 20 km using offshore breakwaters, the energy that can be harvested from waves would be of the order of 100 MW. In addition, point absorbers can be discretely installed along the coastal stretches of the Puducherry territory which are placed apart such as Bommayapalayam on its north and Karaikal on its south.

#### 4.2.1.5 Coast of Andhra Pradesh (Kaviti)

The near shore slope along the Kaviti coast of Andhra Pradesh is relatively steeper. And the available wave power is about 15 kW/m. Wave dragons are recommended at depths of more than 20 m along this coastal stretch and they should be sufficiently close to the shore for effective energy transportation. Hence, the device to be adopted is the wave dragon. A typical sketch of a wave dragon is given below.

**Figure 59: Sketch of Wave Dragon**




*Source: IIT Madras*

### 4.2.2 Summary of Wave Power Estimations in India

Even though technologies and systems have a large improvement in the field of ocean wave energy, the realistic and economical production of energy is remote. The OWC is the simplest and achievable technology in this area. A much greater extent of power is concentrated in the motion of waves than in the movement of air. It produces no greenhouse gases or other waste. Wave energy is naturally concentrated by accumulation over time and space and transported from the point at which it was originally present in the winds.

An overall estimate of the annual energy potential at each of the five identified sites is presented in the table below on the assumption of utilizing 1 km effective stretch of coastal line at each site. It is to be noted that the wave height follows the Rayleigh distribution and hence, the probability of exceedance of design wave height (i.e., significant wave height) is 13% based on average statistics. An estimate is given in the column by considering the plant load factor of 13%. It is to be noted that this value would change if height (Hi) is taken as the average instead of significant wave height (Hs).

**Table 31: Typical estimate of energy harvesting potential for a coastal stretch of 1 km each**

| Sr. No | State/UT | Place | $H_s$(m) | $T_s$(s) | Power (kW/m) | Annual Energy potential (GWh) |
|---|---|---|---|---|---|---|
| 1 | Maharastra | Kudal | 2.37 | 8 | 21.95 | 25.0 |
| 2 | Kerala | Trivandrum | 2.4 | 8.9 | 25.08 | 28.6 |
| 3 | Tamil Nadu | Kanyakumari | 2.4 | 8.3 | 23.39 | 26.6 |
| 4 | Tamil Nadu | Puducherry | 1.67 | 7.77 | 10.59 | 12.1 |
| 5 | Andhra Pradesh | Kaviti | 1.97 | 7.87 | 14.96 | 17.0 |

*Source: IIT Madras*

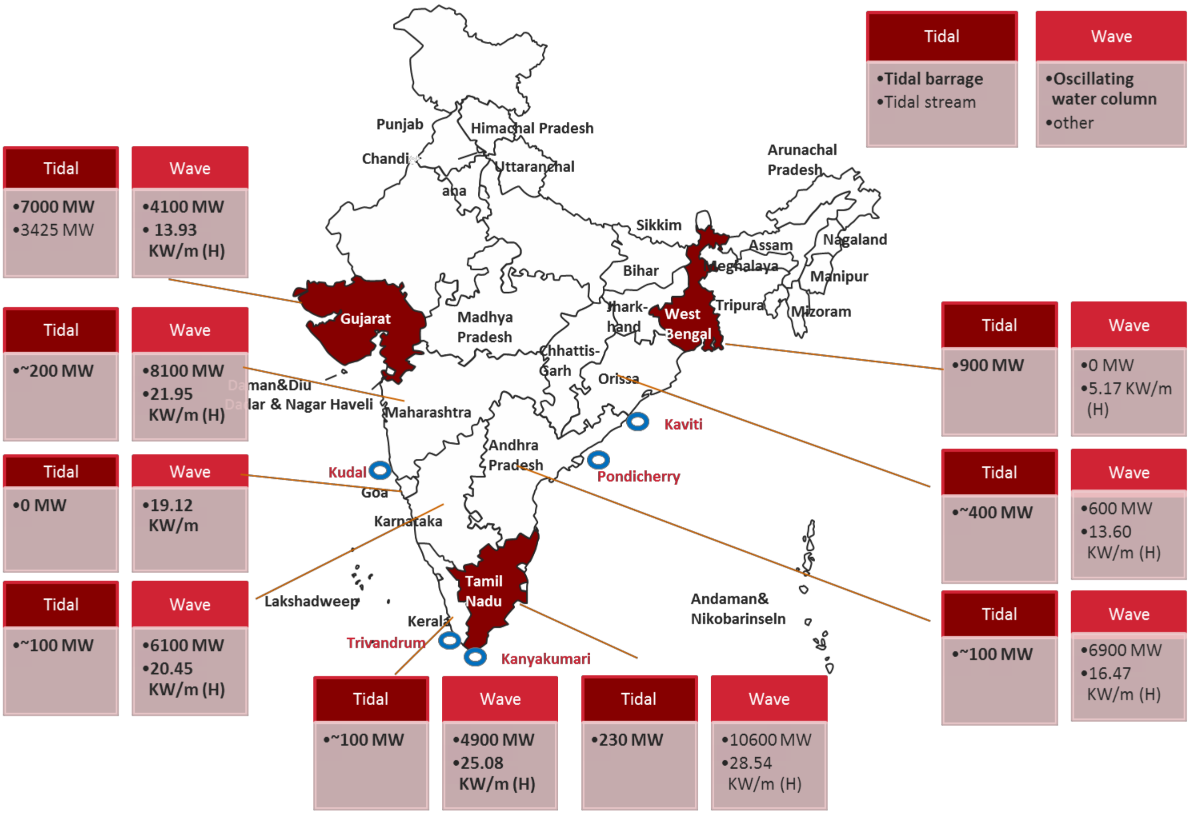
The state wise potential of wave energy is the average potential existing in each state. The average power potential for each meter of the coast is calculated which in turn gives the total power potential along the stretch of the coast for a state. The power potential for each maritime state is brought out in table below.

## Table 32: Summary of state wise wave potential

| State | Total wave Power potential in MW |
|---|---|
| Gujarat | 4100 MW |
| Maharashtra | 8100 MW |
| Kerala | 4900 MW |
| Tamil Nadu | 10600 MW |
| Andhra Pradesh | 6900 MW |
| Orissa | 600 MW |
| Karnataka | 6100 MW |

*Source: IIT Madras and CRIS analysis*

The potential sites and state wise potential of tidal and wave energy is summarized in the map below.



# 5. Cost and Economics of Tidal and Wave Power

The development of wave and tidal technologies has made significant progress in recent years. From prototype development to the installation of first demonstration arrays, a number of companies are taking significant steps towards commercial deployment. However, the industry is still in its early stages, with the most advanced technologies currently undergoing long-term testing to prove reliability, operability and durability of the energy conversion devices. The progression from single demonstration device to the deployment of wave and tidal energy farms or arrays requires technologies to be proven, reliable and affordable.

Tidal technologies appear poised to reach commercialization earlier than wave technologies, since a number of concepts have reached sustained full-scale demonstration. Tidal energy concepts present a greater convergence in design, as the majority of developers are opting for horizontal-axis turbine concepts, thus indicating that the tidal energy sector is reaching a more mature stage of development.

Wave energy devices on the other hand have not reached similar maturity and may benefit from further research and development, innovation and testing before they can be reliably deployed to tap resourceful sites.

Further, development of wave and tidal energy technology is crucial to securing reliable, available, cost-effective deployment. Currently, the development status of the technology is associated with a high levelised cost of energy (LCOE) compared with traditional and other renewable energy sources.

In this section, we will identify the capital and operating costs of tidal and wave power and the levelised cost of generation from such sources of energy. The table below summarizes the capital and operating expenses for tidal and wave power (in real 2010 terms).

**Table 33: Summary of Tidal and Wave Power Costs (in real January 2010 terms)**

| Technology | Pre-demonstration project cost in million (low-high) | Demonstration project cost in million (cost for developers first 10 MW project (low-high) | Commercial project cost in million for developers 10 MW project after 50 MW deployed |
|---|---|---|---|
| **Wave** | | | |
| Capex/MW | € 9.3 (7.8-11.0) | € 6.2 (5.2-7.2) | € 4.3 (3.5-5.0) |
| Opex./MW/yr. | € 0.80 (0.67-0.93) | Euro 0.37 (0.30-0.45) | € 0.25 (0.17-0.24) |
| **Tidal Range** | | | |
| Capex/MW | n/a | n/a | € 2.3 (1.0-3.5) |
| Opex./MW/yr. | n/a | n/a | € 0.025 (0.02-0.03) |
| **Tidal Stream shallow** | | | |
| Capex/MW | € 12.6 (9.5-15.7) | € 5.5 (4.4-6.5) | € 3.9 (2.9-4.95) |
| Opex./MW/yr | € 0.55 (0.40-0.71) | € 0.38 (0.29-0.48) | € 0.20 (0.15-0.24) |
| **Tidal Stream Deep** | | | |
| Capex/MW | € 11.0 (9.3-12.5) | € 4.5 (3.8-5.2) | € 3.9 (2.9-4.95) |
| Opex./MW/year | € 0.41 (0.34-0.50) | € 0.20 (0.15-0.25) | € 0.16 (0.11-0.20) |

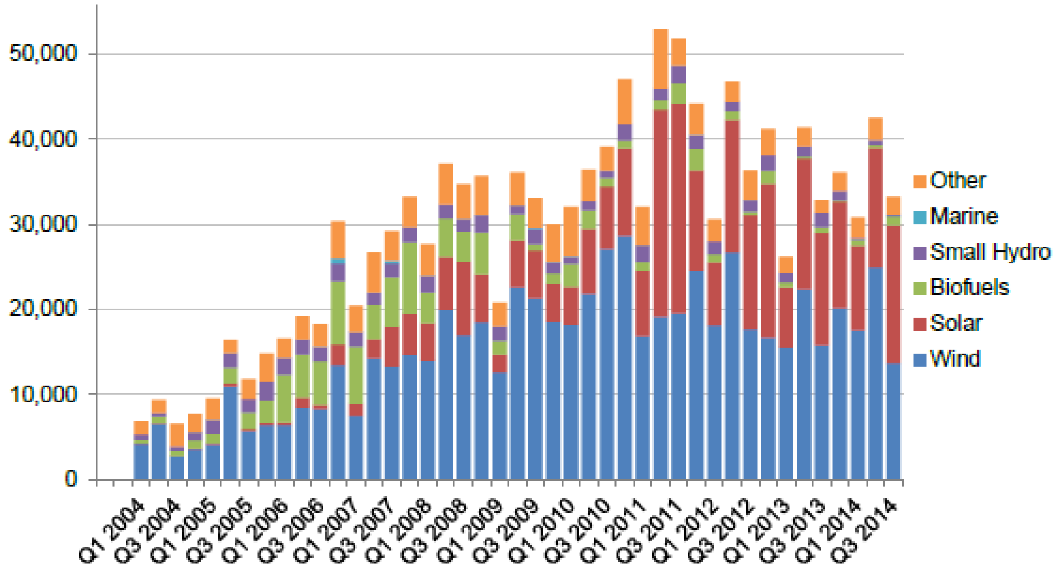
*Source: (Black & Veatch Marine Energy Cost Analysis 2010)*

Marine is amongst the most capital intensive forms of renewable energy. Partly due to its pre-commercial stage of development, the LCOE for marine energy project is difficult to estimate. The best estimates show that it has the highest LCOE due to:

- No scale economies;
- Lower efficiency rates (from fine-tuning);
- No benefit of meaningful debt financing;

**Currently, there is an excess of financial capital in the market but it is quite risk averse. Last quarter over USD 30 billion was raised in the form of project finance for clean energy assets around the world.**

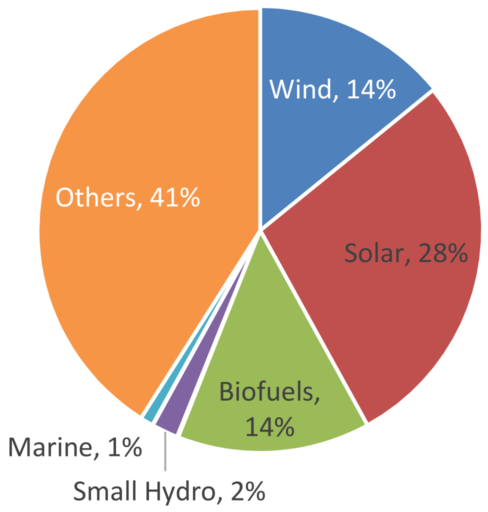
**Figure 60: New Investments in Clean Energy - Project Finance (USD million)**




*Source: Bloomberg New Energy Finance*

**It has been observed that marine energy has attracted only 1% of the total VC/PE capital in the clean energy space over the past ten years.**

**Figure 61 : Cumulative VC/PE investments by sector from first quarter 2004 to third quarter of 2014**




*Source: Bloomberg New Energy Finance*

## 5.1 Capital and Operating Expenditure for Tidal and Wave Power

### 5.1.1 Capital Expenditure (CAPEX)

The capital expenditures (capital costs) for tidal and wave energy development begins long before construction starts. There are six major elements to capital cost: the project itself, the manufacture/supply of turbine(s), its foundation, electrical components, onshore facilities and monitoring equipment, installation and commissioning costs, and decommissioning (Renewable UK, 2011). Each of these elements will be described below.

#### 5.1.1.1 Project Development Costs

A series of activities are necessary to assess the suitability of a site before manufacture and installation of an ocean energy array can proceed: preparation of engineering designs, carrying out costing and obtaining necessary permissions. Project developers must carry out a set of investigations and initial design work, and be granted approval by relevant bodies. Site appraisal activities include:

- Design and feasibility assessments
- Seabed surveys
- Environment surveys, environment impact assessments
- Resource characterizations

Consultation with local residents, the fishing industry and other stakeholders is an on-going process during the development stages and is an important step to gain project approval from statutory bodies in the form of relevant leases and planning consents. The permitting process can take a year or longer, and must be completed before construction can begin. The time it takes to go from application to approval is dependent on the complexity of dealing with multiple planning bodies.

Obtaining an electricity grid connection agreement is an essential step in project development. There may be a long lead time before the grid connection is available.

#### 5.1.1.2 Electricity Conversion Devices

The cost of the electricity conversion devices (EC) includes manufacture or purchase of the device itself and electrical components (electrical systems that connect the device to the array cables). The costs of materials, components and labour in manufacture, fabrication, and assembly of the turbine components are included in this. The costs of transporting the components to a construction port may either be included in the construction cost or in the installation costs. The turbine itself consists of steel and composite materials and requires fabrication. Considerations include water depth, mean water speed, rated power of the turbine, and rotor diameter. The location will also dictate the electrical cable length and the size and design of the foundation.

- **Wave devices**

Wave developers are investigating different structural configurations which could lead to improved yield through better coupling between resource and reaction mass. Wave devices will have a higher yield at more energetic sites which tend to be further from the shore. These sites lead to additional requirements for robustness and reliability and manufacturers are looking to gain initial operating experience in sites with less extreme conditions before developing sites further offshore.

- **Tidal devices**

For tidal turbines, the mechanisms for energy capture are well understood but there are further steps that can be made to optimise sub-component design, for instance, of turbine blades to withstand turbulent conditions. Some of the most energetic tidal sites are very challenging environments which will require heavily engineered structures or new structural concepts such as tethered internally buoyant turbines.

#### 5.1.1.3 Foundation and Moorings

The foundation or moorings make up 6% of typical lifetime costs for an offshore wave array and 14% of lifetime costs for a bottom-mounted tidal array. Costs for floating or neutrally buoyant tidal devices could be lower. The structure needed to fix the turbine in place depends on its design and location: water depth and speed, ground conditions, and the tidal range. It needs to be designed for the maximum load the turbine will encounter so it can stay in place in the roughest conditions (Entec, 2006). The device may be held in place using a concrete gravity base, with a monopole, or supported from the surface.

#### 5.1.1.4 Grid Connection and Transmission Charges

It consist of cables required to interconnect individual devices to a common interconnection point, cables linking to shore, and onshore electrical systems, including onshore cables and a substation at the point of connection to the transmission system, and power quality equipment (inverters, filters). Costs will be dependent upon distance to shore, ground conditions along any cable route, and voltage levels. Whether the costs of the electrical connections are borne by the developer or by the transmission network owner depends on the jurisdiction. Costs will either be capital costs to the developer and associated maintenance costs as part of operating expenses, or be in the form of transmission and wheeling charges paid to the network owner.

#### 5.1.1.5 Tidal / Wave Arrays

To be commercially viable, an array of multiple devices may be needed to obtain sufficient economies of scale. In the case of arrays, there will be additional capital costs (though less per unit) associated with civil engineering infrastructure. The costs will be based on the number of devices installed, their configuration within a farm, and inter-device spacing. As well, in the case of tidal arrays, there may be one or more "redundant" devices, essentially excess capacity at the ready, so the downtime for routine repair and maintenance of individual units does not reduce the farm yield.

#### 5.1.1.6 Onshore Facilities and Equipment

Onshore, there will be need for office and warehouse space. It is likely space can be rented in existing buildings, such as in a nearby industrial park. If leased, rental fees will be part of operating expenses; if built, the cost of construction will be a capital cost. Deployment, retrieval, and maintenance facilities may already exist at a nearby port for other maritime industries.

#### 5.1.1.7 Installation/Deployment

Installation includes the transportation of components to a construction port, onshore preparation, and setting the equipment in place and commissioning (Renewable UK, 2011). The method of installation depends on device design. Some devices may be towed to the site by tugs and anchored with an anchor handler. Others must be carried by a heavy lift vessel or barge or may require an expensive jack-up barge to install them (Entec, 2006). Costs of these can be estimated using vessel charter rates. Timing and availability of some equipment will affect these costs. Sea conditions and the tidal range also affect the choice and cost of vessel. The distance from port will have a bearing on the duration of the vessel charters. In general, installation costs will be influenced by water depth, tidal stream, tidal range, and distance from port. Installation costs will generally increase as the turbines are located further off-shore due to transporting time, size and specialty of equipment required to do the work, and weather-related delays.

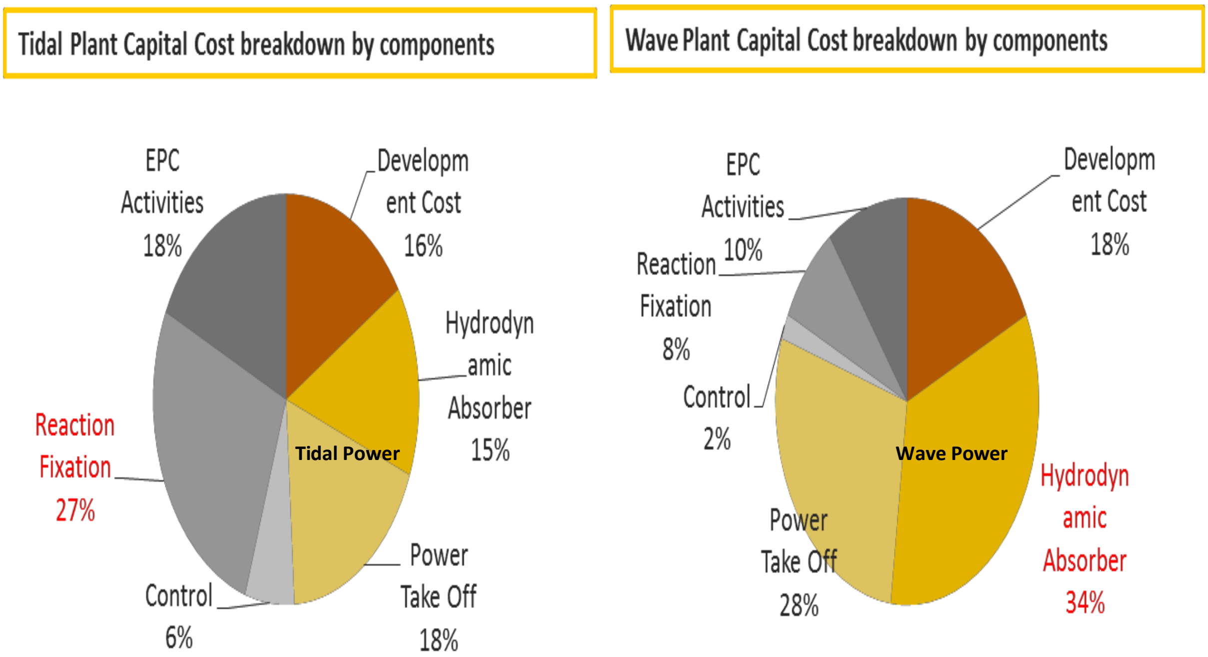
#### 5.1.1.8 Periodic Overhauls and Refits

The turbines and their moving parts (gears, bearings, seals) as well as the mooring cables and parts, will need to be overhauled during the device‟s economic life. When and how often, will depend on their design and the environment they operate in. For instance, overhauls may be scheduled in five-year intervals. Unlike routine and emergency maintenance, overhauls and refits may be considered capital costs and be amortized over the life of the refit.

#### 5.1.1.9 Decommissioning

The costs of decommissioning include removing the device and cable from the water, and restoring the site to its original state. The cost of decommissioning may be defrayed through the reuse, recycle, or sale of the components and materials. The decommissioning expenditure is at the end of the device‟s economic life, which may be 20 years or more; so in present value terms, it is a comparatively small portion of the total CAPEX. It is, however, harder to predict these costs since they occur well into the future.

**Figure 62: CAPEX Breakdown for Tidal & Wave Power Projects**




*Source: Black & Veatch Marine Cost and Performance Data for Power Generation Technologies prepared for NREL, 2012*

## 5.1.2 Operating Expenditure (OPEX)

One of the key advantages of tidal energy is the absence of primary fuel costs. The energy is renewable and provided by the moving water, in contrast to fossil fuels. However, the operating costs are significant and ongoing for the economic life of the turbine. The operating expenses of the tidal energy project are meant for monitoring and for routine and emergency maintenance activities.

### 5.1.2.1 Monitoring

Monitoring occurs both remotely, onshore and on-site, where the turbines are installed. The devices can be equipped with monitoring equipment that can self-test device connection and stability. This data is sent via data cables and accessed online. The impact of the turbine on the local environment must be continually monitored. The costs of monitoring include electrical power, data management, and salaries of skilled employees. There would also be costs of tools and devices, and if on-site checks apply, transportation costs.

### 5.1.2.2 Routine Maintenance

The cost of preventative and routine maintenance depends on many variables, including the number of times it is scheduled, the number of turbines, labour hours per turbine, engineer and technician salaries, distance from shore, transportation costs (vessel charter costs), the need for special vessels, their travelling speed, the cost of electrical and mechanical tools, cleaning and protective equipment, and diagnostic equipment (Li et al., 2011; Renewable UK, 2011). Costs also include those necessary to protect the health and safety of workers. Maintenance costs (and availability) will also depend on the maintenance scheme used, such as whether a service is completed on-site or if the device is returned to the shore for maintenance.

#### 5.1.2.3 Emergency Maintenance

If a breakdown has occurred or one is eminent, unscheduled maintenance or repair work must be undertaken. The costs of emergency maintenance include the cost of replacement materials, plus many of the costs noted in routine maintenance (transportation, labour, etc.). The amount of downtime while crews access and repair the turbine also affects the output of the turbine, thereby affecting the revenues generated from it. Estimating emergency maintenance costs is difficult for new technology. Reliability is estimated during the design stage, based on tank tests and sea trials. As the technology matures, the frequency of failure and time to repair will be reduced and be more predictable (EquiMar Work Package 7, 2009, p. 3-3). The key cost drivers of emergency maintenance include failure rates, severity of the failure, replacement cost of the broken components, turbine downtime, equipment needed (special vessels, cranes), skilled labour costs, accessibility of the materials needed for the repair, and accessibility of the turbine (Li et al., 2011). While there is an absence of warranties on these new technologies, these costs will often be borne by the project developer. Weather and sea states add a level of uncertainty and variability to operating and maintenance (O&M) costs. The threshold of wind and water speeds for work to be done onsite and of sufficient duration to complete the work need to be determined.

#### 5.1.2.4 Other Operating Costs

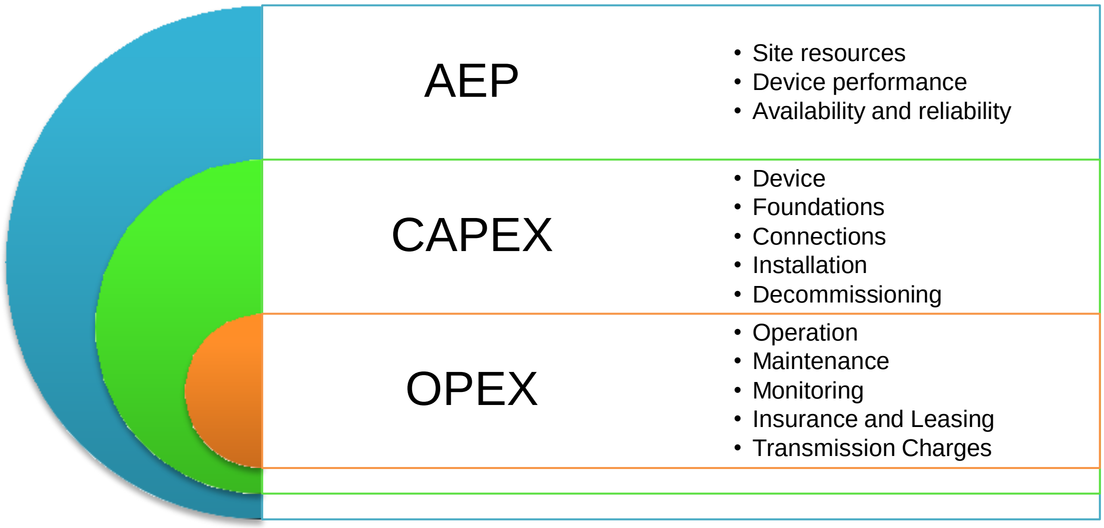
Other operating costs may include rental (or related ownership costs) of space for the control centre, warehousing costs of components, port berthing fees, insurance, legal and accounting fees, bank charges, amortization, audit fees, seabed lease fees and transmission network charges, if applicable.

## 5.2 Economics

### 5.2.1 LCOE of Tidal and Wave Power

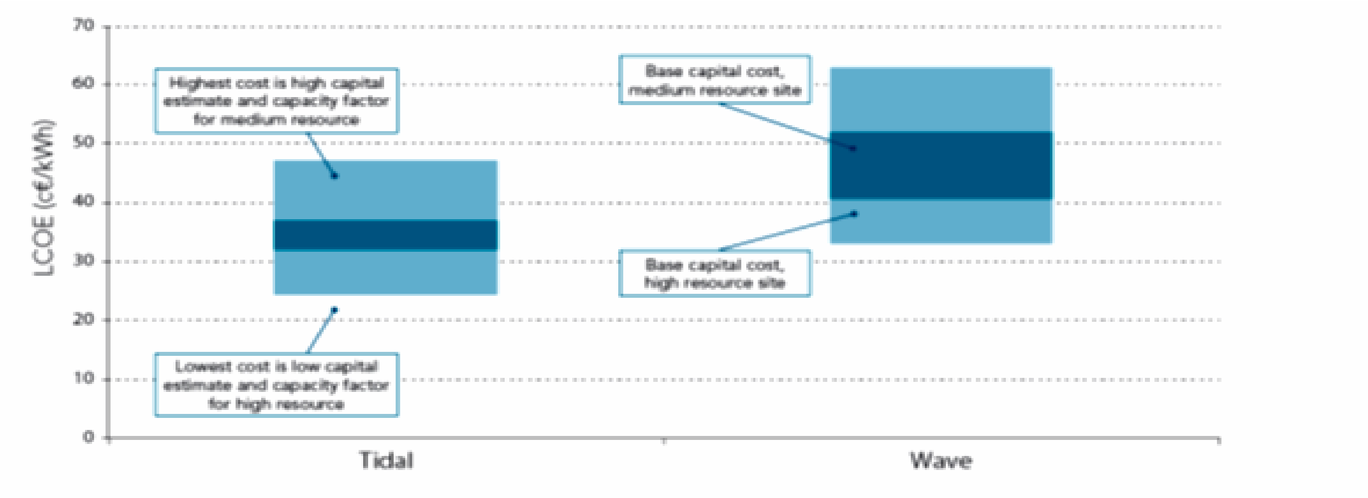
The levelised cost of energy (LCOE) provides an estimate of the cost of electricity from a farm of devices over the life of the asset, and it is reflective of the capital cost, operating cost, decommissioning cost and expected annual energy production (AEP).

**Figure 63: Components of the LCOE**




*Source: SI Ocean, Cost of Energy Report, 2013*

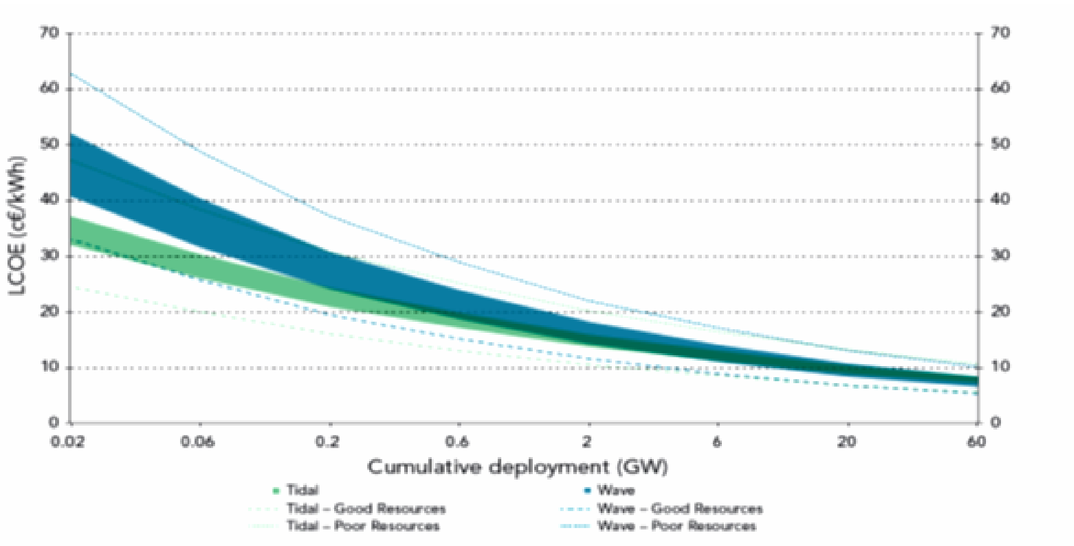
**Figure 64: Early Array Costs**




*Source: SI Ocean, Cost of Energy Report, 2013*

Estimates of the LCOE for early arrays have been determined for both tidal and wave energy technology. Early array costs are based on data from SI Ocean and Black and Veatch. As can be seen in Figure 4, the LCOE for early tidal energy arrays varies between 24 and 47 c€/kWh, whilst the current cost range for wave energy arrays ranges between 34 and 63 c€/kWh. The need for competitiveness with alternative energy technologies requires concrete actions that will reduce the LCOE to more competitive values. LCOE predictions (Figure 5) based on a 12% learning rate and cumulative deployment indicate that tidal technologies could achieve commercial competitiveness with other renewable energy sources once approximately 5 GW of cumulative capacity has been installed. Wave technologies, on the other hand, would require a cumulative capacity of over 10 GW to become cost-competitive. Currently, however, both estimates appear quite challenging for the industry. These predictions were developed considering as a starting point a cumulative deployment of 20 MW for both technologies, and could be achieved if common design consensus is reached.

**Figure 65: LCOE Predictions as per SI OCEAN**




*Source: SI Ocean, Cost of Energy Report, 2013*

It should be noted that the overall deployment capacity for wave energy far exceeds that of tidal. The global wave resource is significantly greater than the tidal resource across the same geographic area

(29,500TWh/year vs. 1,200TWh/year). While tidal energy is dependent on geographic conditions and is site-specific, wave energy is much more prevalent along a given west-facing coastline with significant fetch length. As a result, it is anticipated that in the long term, wave energy LCOE will fall to a similar level to the cost of tidal energy once the technology has reached maturity. It is important to highlight that cost reduction can be achieved through a series of mechanisms that fit with the continuous development of tidal and wave energy technologies, in particular:

- Performance improvement: Improved energy capture from individual devices and arrays, and much better reliability, resulting in increased energy yield and economic return
- Upscaling: Scale and volume production give room for cost-reduction opportunities. These can be achieved through the up-scaling of devices (lower cost/capacity) and increasing number of devices (lower installation cost per device), thus driving reduction through scale of production and scale of engineering support.
- Experience: Increased know-how, gained through learning-by-doing, allows for optimisation of production, installation and O&M of ocean energy arrays. In particular, increased reliability (track record of installation) will play a significant role in risk perception and project cost assessment.
- Innovation: Innovation of device components or production mechanisms could allow new solutions (such as materials) to emerge, potentially helping to bring down the cost associated with ocean energy arrays.

### 5.2.2 Estimated Costs for Existing and Proposed Tidal Schemes

Tidal range energy has been commercially applied since the late 1960s in France, and most recently in South Korea. With regard to the tidal range, the upfront costs associated with installation are high; however, over a longer term, they offer good payback.

The two main cost factors are: the size of the barrage (length and height) determining the capital costs, and the difference in height between high and low tide that determines electricity production.

The Sihwa power plant in South Korea is the largest tidal range installation in the world, it is estimated to cost around € 240 million. The construction costs, however, do not necessarily need to be assigned to power production. In the case of La Rance, the construction also functions as a highway, reducing travel distance by 30 km for up to 60,000 vehicles per day (De Laleu, 2009). Similarly, the Sihwa lake tidal barrage is constructed on top of an existing dam. Besides the upfront costs, other considerable costs may be the control, monitoring and management of the ecological status within the impoundment. A comparison of existing and proposed tidal barrages is provided in the table below.

**Table 34: Estimated Construction Costs for Existing and Proposed Tidal Barrages**

| Barrages | Country | Capacity (MW) | Power Generation (GWh) | Load Factor (%age) | CapEx (€ million) | CapEx (€ million /MW) |
|---|---|---|---|---|---|---|
| **Operating** | | | | | | |
| La Rance | France | 240 | 540 | 26% | 790 | 3.29 |
| Sihwa Lake | Korea | 254 | 552 | 25% | 238 | 0.94 |
| **Proposed / Planned** | | | | | | |
| Wyre Barrage | UK | 61.4 | 131 | 24% | 262 | 4.27 |

| Barrages | Country | Capacity (MW) | Power Generation (GWh) | Load Factor (%age) | CapEx (€ million) | CapEx (€ million /MW) |
|---|---|---|---|---|---|---|
| Garorim Bay | Korea | 520 | 950 | 21% | 640 | 1.23 |
| Mersey Barrage | UK | 700 | 1340 | 22% | 4,593 | 6.56 |
| Incheon | Korea | 1320 | 2410 | 21% | 3,018 | 2.29 |
| Dalupiri Blue | Philippi n es | 2200 | 4000 | 21% | 2,427 | 1.10 |
| Severn Barrage | UK | 8640 | 15600 | 21% | 28,868 | 3.34 |
| Penzhina Bay | Russia | 87000 | 200000 | 26% | 2,62,453 | 3.02 |

*Source: IRENA report on Tidal Energy 2014*

The development of commercial arrays of tidal current technologies is still in the demonstration phase, so levelised costs of electricity (LCOE) are in the range of € 0.20-0.50/kWh with the lower range LCOE estimates based on medium-high capacity factors and low capital cost estimates (SI Ocean, 2014).

**Table 35: Estimated Construction Costs for Existing and Proposed Tidal Stream Projects**

| Tidal Stream | Countr y | Capacity (MW) | Capex (€ Million) | Capex (€ million/MW) |
|---|---|---|---|---|
| Strangford (Operating) | UK | 1.2 | 7.9 | 6.6 |
| Atlantis GPCL JV (proposed) | India | 50.0 | 144.0 | 2.9 |

*Source: IRENA report on Tidal Energy 2014*

The Carbon Trust indicates that the highest current costs are related to installation (35%), structure (15%), and maintenance and operation (15%), with installation costs varying greatly according to the location (Carbon Trust, 2012). Costs are projected to come down with deployment levels and resource quality as the important determinants. Furthermore, technology developers are working hard to increase the capacity factor of arrays from around 25% to 40% and the availability factor from 70% to 90% by 2020 (ETI/UKERC, 2014). If deployment is in the order of 200 MW by 2020, SI Ocean estimates an LCOE with a central range of EUR 0.18-0.25/kWh (SI Ocean, 2013a). These estimates are similar to a study by the Carbon Trust, which estimated that the costs for tidal current devices will be around EUR 0.17-0.23/kWh in 2020 (Carbon Trust, 2012). Deployment in high or low quality resource area can increase this range to EUR 0.16-0.30/kWh (SI Ocean, 2013a). Scaling up to around 2-4 GW – assumed to be possible by 2030 – could bring LCOE below EUR 0.20/kWh (Carbon Trust, 2012; SI Ocean, 2013).

### 5.2.3 Case Study – 50 MW Proposed Pilot at Gulf of Kutch (Atlantis & GPCL JV)

**Project Description**

In 2011, the Government of Gujarat entered into an MoU with Atlantis Resources (Gujarat Tidal) Pte limited (Joint venture of GPCL, Atlantis & PMES) for carrying out further studies and for implementing a 50 MW pilot tidal-based power project in the Gulf of Kutch at Mandvi. The Government of Gujarat sanctioned INR 700 million (EUR 9 million) as financial assistance for the project.

**Current Status**

The project has obtained the required clearances from the Department of Fisheries, Gujarat Maritime board, and Coast Guard and has obtained power evacuation approval for 50 MW.

- Completed rapid EIA / EMP report through the National Institute of Oceanography (NIO)
- Carrying out final testing of the turbine at the Narec test facility in the UK
- The Forest and Environment Department, Government of Gujarat has forwarded its recommendations to the Forest and Environment Department, Government of India for this project.
- Work pertaining to tariff petition is going on before the Gujarat State Regulatory Commission.
- The CRZ Committee has decided to recommend the project for CRZ clearance in its meeting held on 21-11-2013.
- Because of financing challenges, the project has been put on hold.

**LCOE Calculation**

Following are the project cost and performance parameters used by Atlantis for tariff approval. Based on the calculations, Atlantis had proposed a tariff of INR 13/u (€ 17/u) to the Electricity Regulatory commission in Gujarat.

**Table 36: LOCE for Proposed Plant in Gujarat**

| Key Parameters | Units | |
|---|---|---|
| **Capacity** | MW | 50 |
| **CAPEX/ Installed Capacity** | Euro million / MW | 2.88 |
| **Total CAPEX** | Euro million | 144.24 |
| **Average Annual Maintenance costs as % of installed costs** | % | 12.90% |
| **Average Annual Other Operating costs** | % | 0.80% |
| **Capacity Utilization Factor** | % | 25% |
| **Availability Factor** | % | 90% |
| **System Losses and Downtime** | % | 5.3% |
| **Average Power Output** | kWh per turbine | 213 |
| **Useful Life** | Years | 20 |
| **Debt** | % | 70% |
| **Equity** | % | 30% |
| **Repayment Period (including 7 year of Moratorium)** | years | 21 |

| Key Parameters | Units | |
|---|---|---|
| **Debt Interest Rate** | % | 8% |
| **Tariff Period** | years | 25 |
| **Discount rate for tariff** | % | 10.19% |
| **LCOE*** | **Euro / units** | **€ 0.17 (INR 13)** |

*Source: CRIS Analysis*

*It must be noted that the LCOE for tidal stream in the Indian context is INR 13/u majorly on account of cheaper debt financing (8% instead of 12-13% domestic debt interest rates) and a long debt repayment period (21 years with 7-year moratorium). With Indian financing terms the LCOE for the tidal stream project is in the range of INR 20-25 /u (EURO 0.25 – 0.32).

## 5.3 Conclusion

The development of wave and tidal technology has made significant progress in recent years. A number of companies are moving from prototype development to the installation of first demonstration arrays, a significant step forward towards commercial deployment. The predicted cost of energy from first arrays is relatively high compared to other renewables at a more advanced stage of development (such as offshore wind) but rapid reduction in costs from prototypes is already evident and there is reason to expect significant reduction in cost of energy will continue as deployment increases. Credible paths to reduce capital and operating costs and to increase yield have been identified. Early array costs for wave energy are higher than for tidal, but in the long term, wave energy has larger overall resource potential and so could deliver at similar LCOE to the long-term tidal estimates.

Risk, and perception of risk, has a significant impact on cost estimates for the sector. Wave and tidal energy is currently seen as high risk because of lack of operational experience and this has an impact in terms of higher hurdle rate requirements. There is a need to build up reliability and operation experience to increase certainty in LCOE estimates and reduce risk for investors. Support for early deployment will be crucial as the most rapid cost reductions are expected in the first 10s of MW deployed.

In the Indian context, regulators must promote the development of tidal and wave energy through appropriate feed-in-tariff mechanisms and capital support (soft loan or grants). As was seen in the example of the tidal stream project of Atlantis and GPCL, the LCOE can vary significantly depending on the cost and tenure of financing.

# 6. Environment Assessment

This chapter briefly describes the existing legal and regulatory framework in countries that are promoting the development wave and tidal energy projects. Further, this chapter also presents the different policy and financial incentives available in these countries for wave and tidal energy sector. In the second section, the existing legal and regulatory framework in India for promotion of power generation from renewable energy sources has been discussed. Further, the overall impact of various financial incentives on the development of the renewable energy sector in India has been captured. The chapter also attempts to explore various funding sources, project selection strategies and their applicability to tidal and wave energy projects in India.

## 6.1 Assessment of Environment for Marine Energy – International

### 6.1.1 Europe – Strategic Initiative for Ocean Energy

The Strategic Initiative for Ocean Energy (SI Ocean)[11] was launched at International Conference on Ocean Energy 2012 conference in Dublin as a 2-year project from June 2012 to June 2014 to deliver a common strategy for ensuring development of maximum wave and tidal energy based power projects by 2020, paving the way for exponential market growth in the year 2030 and year 2050 in Europe.

The project was funded by the European Commission's Intelligent Energy Europe programme. The project consortium consisted of seven members: Ocean Energy Europe (Belgium), European Commission Joint Research Centre (JRC), Europe; Renewable UK, Carbon Trust, and University of Edinburgh (UK); WavEC (Portugal); and Danish Hydro graphic Institute (Denmark).

SI Ocean focuses on high resource areas of the „Atlantic Arc‟ region, spanning the western facing Atlantic coastline and the northern area of the North Sea, encompassing the territorial waters of Denmark, France, Ireland, Portugal, Spain and the United Kingdom. The key deliverables for the project were to assess:

- Possible ocean energy resource in the selected region;
- Existing and upcoming technology options supporting commercialisation of wave and tidal devices;
- Policy and market barriers for deployment and commercialization of wave and tidal energy.

Based on the 2-year study, the consortium prepared detailed reports on the following aspects to promote the development of wave and tidal energy in Europe.

- Wave and tidal resource energy interface;
- Energy projections for 2020/2030/2050;
- Detailed review of wave and tidal technology;
- Cost of energy and cost reduction options;

[11] *Source: www.si-ocean.eu*

- Required regulatory and policy interventions.

These outcomes were discussed in a culminating workshop in June 2014 and are being utilised by the consortium countries for the development of ocean energy in the identified region.

### 6.1.2 United Kingdom

#### Overview

Currently, the United Kingdom (UK) is the foremost runner in the field of marine energy development comprising wave and tidal energy projects. As per the potential assessment, the wave and tidal energy can meet up to 20% of the UK‟s current electricity demand i.e. ~30-50 GW installed capacity. Also known as the „Saudi Arabia of marine energy‟, the UK can largely benefit by developing the enormous untapped marine energy potential in the region. Around 700 MW of wave projects and 1000 MW of tidal projects are under various stages of development in the UK region. Some of the key projects are listed in the table below.

**Table 37: Tidal & Wave Energy Projects in UK**

| Location | Technology | Capacity | Development Stage |
|---|---|---|---|
| Pentland Firth and OrkneyWaters, Scotland | Wave | 200 MW | Under development |
| | | 200 MW | Under development |
| | | 50 MW | Under development |
| | | 50 MW | Under development |
| Pentland Firth and Orkney Waters, Scotland | Tidal | 400 MW | Under development |
| | | 200 MW | Under development |
| | | 100 MW | Under development |
| Pembrokeshire, Wales | | 10 MW | Under Planning |

*Source: Press Releases*

#### Policy & Incentive Framework

The government of England and Scotland has also developed supportive policy and regulatory structures to promote wave and tidal energy projects in the UK. Marine energy has been highlighted as one of the eight technologies to be developed as part of the „UK Renewables Roadmap‟ 2020. As per the roadmap, the UK authorities are targeting 200-300 MW of wave and tidal energy projects deployment by 2020 which will be further scaled up to 27 GW by 2050. The key highlights of roadmap are:

- **Demonstration Funding:** The Department of Energy & Climate Change (DECC) sanctioned capital grants to the tune of £20 million under the Marine Energy Array Demonstrator scheme to support two projects.
- **Renewable Obligation Certificates**: Wave and tidal energy projects have been covered under the Renewable Obligations Certificate (ROC) system. As a part of new ROC band system, 5 ROCs will be issued for each MWh of energy generated at wave and tidal projects in the UK. These ROCs will be procured by licensed suppliers of electricity in the UK from the trading exchanges.

- **Research Funding Grants**: The governments of England and Scotland provide support in the form of grant funding for research and development activities in marine energy field. For example, the Scottish government announced an £18 million grant to support marine energy development under the Marine Renewables Commercialization Fund (MRCF).
- **Loans and Guarantees:** The Government of UK region also provides support in the form of loans and guarantees for wave and tidal projects. For example, the Renewable Energy Investment Fund (REIF) offers a total of £103 million in loans, equity investments and guarantees for renewable energy sector projects in Scotland.
- **Other Initiatives:** The Scottish government offers the „Saltire Prize‟ from a £10 million fund to most energy generating wave and tidal projects in Scotland for a continuous two-year period between 2012 and 2017.
- **New Reforms:** The UK regulators are further planning to introduce FIT with contracts for difference (CFD) for tidal and wave energy projects.

The government is strongly committed to marine energy development in the UK region with a focus on reducing the cost of generation in the small and medium term horizons with small-scale projects followed by large-scale projects.

### 6.1.3 France

France is one of the leading nations in the field of ocean energy development. Under the European Directive 28 / EC / 2009, on the implementation of the Grenelle Environment, France has committed to increase the share of renewable energy to at least 23% of its total energy consumption by 2020, with a 3% contribution from marine energy. France has the experience of operating world‟s second largest tidal energy power plant, with a power capacity of 240 MW, in the Rance estuary since 1966. Apart from the La Rance project, a number of projects have been proposed for exploring the tidal and wave energy potential. Some of the key projects are listed in the table below.

**Table 38: Tidal and Wave Energy Projects in France**

| Location | Technology | Capacity | Development Stage |
|---|---|---|---|
| Atlantic Coast (Pimpol-Bréhat) | Tidal | 2.5 MW | Early stage of development |
| Atlantic Coast (Brittany) | Tidal | 0.5 MW | Early stage of development |
| Atlantic Coast (Pimpol-Bréhat) | Tidal | 1 MW | Early stage of development |
| Atlantic Coast (Normandy) | Tidal | 3-10 MW | Early stage of development |
| Atlantic Coast (Brittany) | Tidal | NA | Early stage of development |
| Atlantic Coast (Brittany) | Wave | NA | Early stage of development |

*Source: Press Releases*

#### Policy & Incentive Framework

The Ministry of Ecology, Sustainable Development & Energy and the Ministry of Economy & Finance issued a report on the development of ocean energy in France. As a part of the „National Action Plan for Promotion of Renewable Energies 2009-20‟, the Government of France has provided the following incentives for promoting ocean energy (wave, tidal, and ocean current):

- **Purchase Price**: A renewable feed-in tariff (REFIT) to the tune of 173 Euros has been fixed for procurement of 1 MWh of marine / ocean energy. In the later years, industrial sites for wave and tidal energy will be awarded by a competitive bidding under the Energy Regulation Commission (ERC).

- **Demonstration Funding:** The Government of France provides funds through the Agence de l‟Environnement et de la Maîtrise de l‟Énergie (ADEME) for supporting testing and experimentation of upcoming technologies by creating demonstrators. For example, ADEME co-financed the construction of five demonstrators by Investing for the Future program.
- **Digressive / Exceptional Depreciation:** Material required for enabling the use of tidal, wave and thermal energy from the sea and its storage are subjected to digressive or exceptional depreciation over 12 months as per the General Tax Code. This enables the developer to deduct annual investments higher than that of the digressive depreciation to save tax.
- **Renewable Energy Certificates**: The Renewable Energy Certificate (REC) system is a harmonised European system of traceability and certification for electricity of renewable origin. These certificates can be traded on power exchanges and hence improve project viability.
- **Research Funding Grants**: The Government of France also provides long-term grants for funding research and development activities in the field of ocean energy. For example, the institute France Energies Marines created in 2012 by the French government is being financed by the government up to € 34.3 million over a 10-year period. France Energies Marines is a collaboration of wide range of relevant stakeholders including but not limited to private companies, research organizations and higher education institutions involved in research and development activities.

### 6.1.4 Canada

Canada has world‟s largest coastline covering around 200,000 km and hence offers great opportunities in the field of marine energy development. As per the Marine Renewable Energy Technology Roadmap developed by the Canadian government, Canada has a wave energy potential of nearly 36 GW, more than 25% of Canada‟s electricity demand. The following table provides a snapshot of marine energy potential in Canada.

**Table 39: Marine Energy Potential in Canada**

| | In-stream Tidal | River-current | Wave | Total |
|---|---|---|---|---|
| **Extractable Mean Potential** | ~6,300 MW | > 2,000 MW | ~ 27,500 MW | **~ 35,800 MW** |

*Source: Marine Renewable Energy Technology Roadmap*

Currently, around 22 MW of tidal projects are operational in Canada and a number of projects are in planning and development phases. The following table provides a snapshot of operational projects in Canada.

**Table 40: Operational Tidal Projects in Canada**

| Location | Technology | Capacity | Development Stage |
|---|---|---|---|
| Annapolis Royal | Tidal | 20 MW | Operational |
| East River, Nova Scotia | Tidal | 2.1 MW | Operational |

*Source: Marine Renewable Energy Technology Roadmap*

#### Policy & Incentive Framework

The Canadian government has developed a capacity addition roadmap under the Marine Renewable Energy Technology Roadmap. As per the roadmap, Canada will have a generating capacity of 75 MW by 2016, 250 MW by 2020 and 2,000 MW by 2030 from marine energy sources. The roadmap further aims to establish Canada as the leader in development and demonstration of integrated resource assessment, site assessment, installation, and operations and maintenance of marine renewable energy systems. In order to promote such large-scale investments in wave and tidal technologies, the Canadian government provides the following support mechanisms:

- **Feed-in tariff:** The Government of Canada offers an aggressive FIT of 65.2 cents/kWh for community-based projects under the Community FIT (COMFIT) programme. Further, a Developmental Tidal FIT programme similar to the COMFIT programme has been proposed for development of specific renewable energy projects by guaranteeing fixed cost for per unit of generation from in-stream tidal single device projects or arrays greater than 500 kW.
- **Grants & Subsidies:** Grants and subsidies are provided under the Marine Renewable Energy Enabling Measures programme for the development of a policy framework for administering renewable energy activity in the federal offshore. For example, Atlantis Resources Corporation was awarded a $5 million grant by the Canadian government‟s Sustainable Development Technology Canada fund for a megawatt-scale tidal energy project in the Bay of Fundy.
- **Research Funding Grants:** The government also provides grants for conducting research and development activities for marine energy projects in the country. The Nova Scotia Department of Energy provided over $5 million in grants to Offshore Energy Research Association for 15 marine renewable energy projects under tidal energy programme. Nova Scotia Power tested a 1 MW Open Hydro turbine at the Bay of Fundy between November 2009 and December 2010 under the Fundy Ocean Research Center for Energy (FORCE).

### 6.1.5 Other Countries

Apart from countries discussed in the above section, a number of countries are working actively in the field of marine energy for exploring the wave and tidal energy potential. The following table provides a snapshot of enabling framework present in countries who are leaders in marine energy technology.

**Table 41: Snapshot of enabling framework present in various countries**

| Country | Tidal Energy Targets | Revenue Options | Open Sea Testing Centre | Loans, Subsidies & Guarantees | R & D and Demonstration Funding |
|---|---|---|---|---|---|
| **UK** | Specified under the RE Roadmap | No Feed-in-Tariff (FIT) ; Covered under ROC Scheme | Yes | Yes | Yes |
| **France** | Specified under the European Directive | FIT available ($Cent 22 / unit); Covered under Renewable Energy Certificate (REC) Scheme | Yes | Yes | Yes |
| **Canada** | Specified under Marine RE Technology Roadmap | FIT available ($Cent 56 /unit) | Yes | Yes | Yes |

| Country | Tidal Energy Targets | Revenue Options | Open Sea Testing Centre | Loans, Subsidies & Guarantees | R & D and Demonstration Funding |
|---|---|---|---|---|---|
| **South Korea** | Defined under RE plan | No FIT; Covered under RPS Scheme | No | Yes | Yes |
| **Ireland** | Defined under National RE Action Plan | FIT available ($Cent 56 /unit) | Yes | Yes | Yes |
| **China** | 2030 Strategic roadmap under development | FIT available | Under development | Yes | Yes |
| **Denmark** | No | FIT available ($Cent 10 /unit) | Yes | Yes | Yes |
| **USA** | No | No FIT; Covered under Clean Energy bonds | Yes | No | Yes |

*Source: SI Ocean, 2013 and CRIS analysis*

Despite the efforts being made by various national governments, the tidal and wave energy sector faces a number of issues which need to be resolved for promoting marine energy resources. Some of the key barriers in the development of tidal and wave energy projects are outlined below.

## Technological Barriers

Low turbine efficiency and high equipment costs are two major technological hurdles that need to be addressed for achieving worldwide commercial success for the marine energy sector. Lack of experience, unpredictable environmental conditions and information of machine performance are areas of concern. Therefore, they need to be looked into to promote marine energy as a viable alternative to conventional energy.

Experience in similar technologies such as offshore wind and oil projects needs to be factored in for identifying and resolving risks associated with marine projects. Further, investments in research and development of new technologies, designs, prototype testing, and pilot projects will be required to make marine energy an economical source of energy generation in the coming years.

## Environmental Barriers

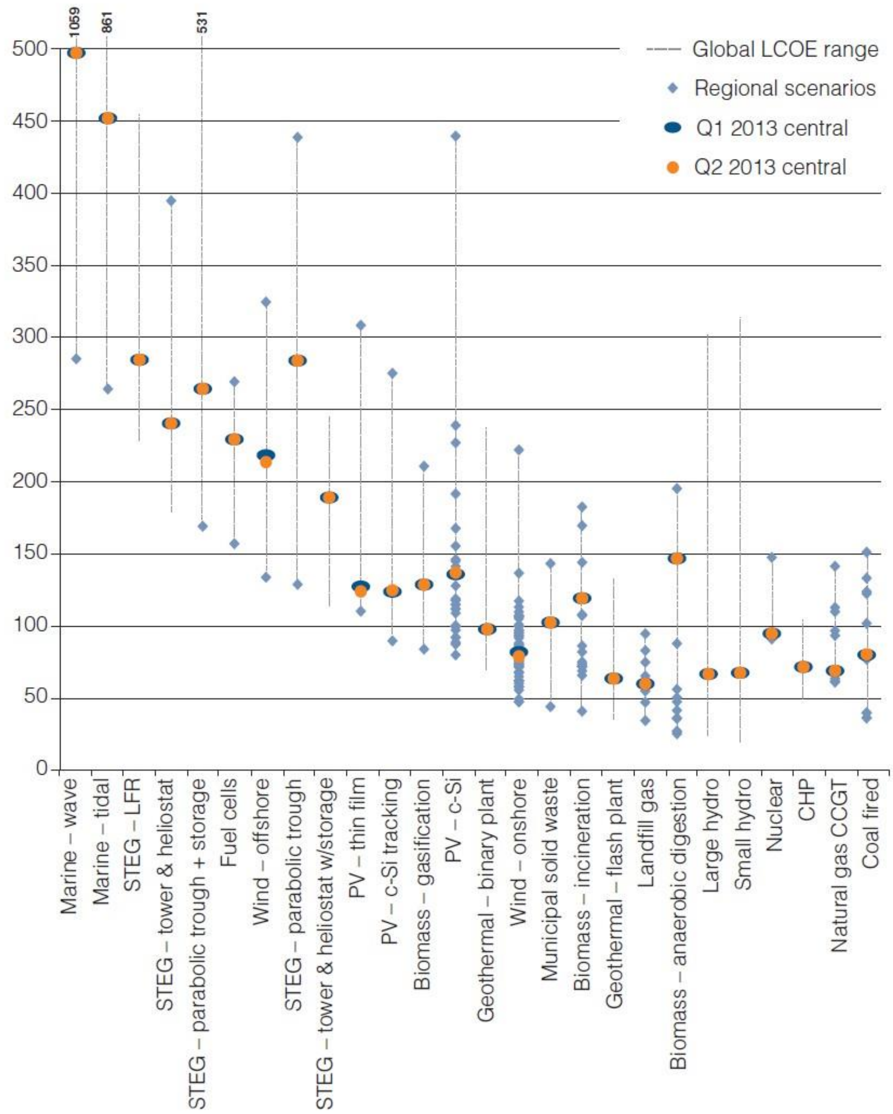
The marine energy power projects may have an adverse impact on marine ecosystems, fishing and coastal economic activities. Improper siting of turbines may impact the waves pattern, water body substrate, and natural habitats of aquatic flora and fauna due to the increase in noise level, emissions, and toxic materials, during installation, operations and decommissioning of tidal and wave power projects.

Hence, it is of utmost importance to monitor the marine projects starting from installation of pilot projects to understand their impact on the ecosystem including effects on fish and marine life. Use of video cameras, drift nets, sonar, telemetry, and similar measuring equipments should be promoted in pilot as well as commercial scale projects. This would enable project developers and other stakeholders in exploring possible mitigation options.

## Financing Barriers

Marine energy is amongst the most capital intensive forms of renewable energy based on factors such as capital intensity and levelised cost of electricity. As shown in the figure below, tidal and wave energy are amongst the costliest renewable energy technologies in the world in terms of capital expenditure ($ million per MW).

**Figure 66: Comparison of cost of power generated from renewable sources ($/MWh)**




*Source: Bloomberg, New Energy Finance, World Energy Council*

Currently, most of the tidal and wave energy projects are being funded through a combination of government grants/subsidies and project developer investments. Most of the countries are providing funds for research, development, and project demonstration activities. Further, incentives in the form of FIT, RECs and tax incentives are also being provided in selected countries.

However, due to lack of interest of major financial institutions, there have been no major investments from financial institutions in marine energy projects. Lack of operational experience and project bankability issues make these projects more risky as compared to other renewable energy projects.

Hence, there is a need to promote awareness among financial institutions and prospective lenders about the various existing and upcoming technologies in marine energy generation. Further, the governments need to develop various possible frameworks for promoting marine energy. For example, a number of countries that are active in the marine energy sector have not specified any concrete targets and project viability mechanisms such as FITs. Furthermore, suitable risk sharing/mitigating mechanisms need to be explored to reduce the overall project costs.

**Table 42: Significant barriers to promote marine energy development and steps to be taken**

| Barriers | Concerns | Steps being taken |
|---|---|---|
| **Technological** | ▪ Low turbine efficiency and high equipment costs key bottlenecks<br>▪ Lack of implementation experience, unpredictable environmental conditions needs to be addressed<br>▪ Experience in offshore wind and oil projects to be factored.<br>▪ Investments in R&D of new technologies, designs, prototype testing required | ▪ Capital support being provided for conducting R&D, testing, prototype and pilot array deployment.<br>▪ Focus to be shifted on cost reduction through standardization and economies of scale. |
| **Environmental** | ▪ Impact on marine ecosystems, fishing & coastal economic activities to be studied.<br>▪ Monitoring marine projects to understand impact on ecosystem | ▪ Use of video cameras, drift nets, sonar, telemetry, etc. for pilot as scale projects.<br>▪ Mitigation measures are being explored to reduce / contain the impact on marine life. |
| **Financing** | ▪ Marine energy amongst most capital intensive forms of RE.<br>▪ Lack of interest of financial institutions is a key concern<br>▪ Lack of operational experience and project bankability issues key deterrents for investors.<br>▪ Suitable risk sharing / mitigating mechanisms to be explored to reduce overall project costs. | ▪ Projects are being funded through combination of Government grants / subsidies and project developer investments.<br>▪ Awareness creation among financial institutions and prospective lenders on various existing and upcoming technologies<br>▪ Revenue generation through FITs |

Source: CRIS analysis

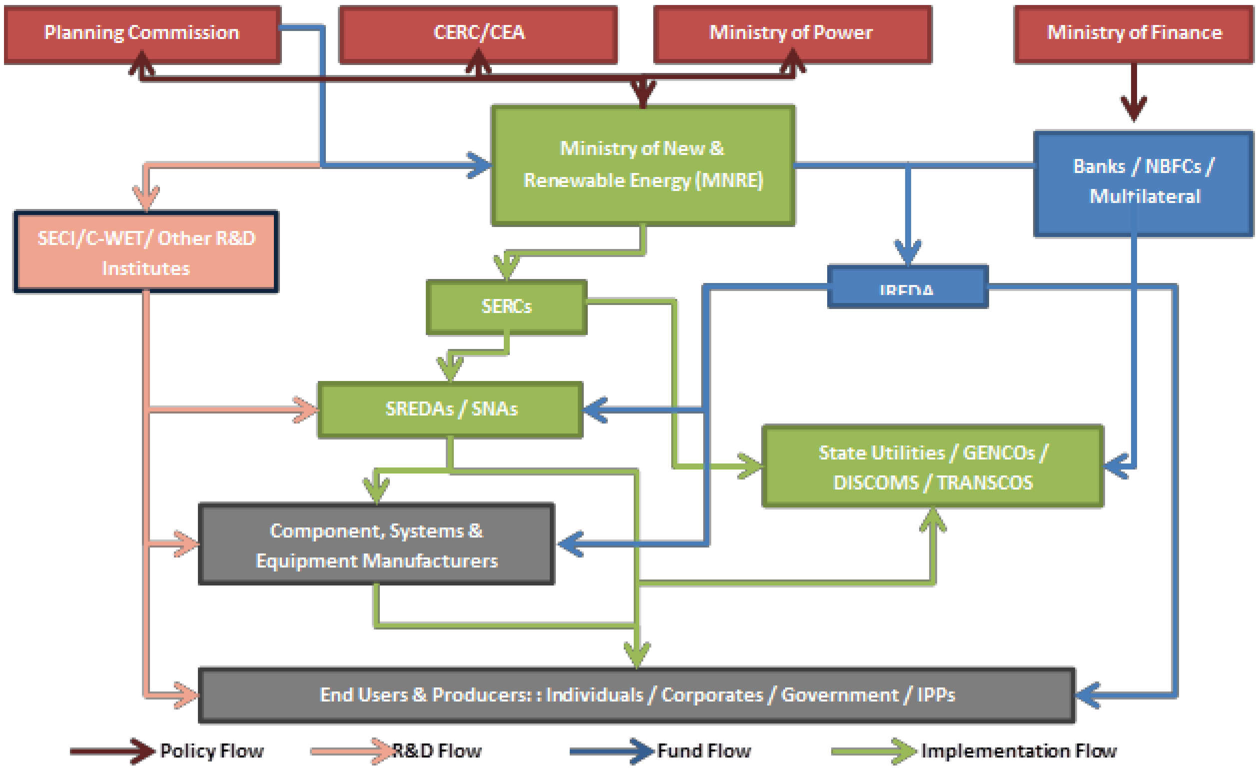
## 6.2 Assessment of Environment for Renewable Energy – India

### 6.2.1 Institutional Framework

The Indian renewable energy sector encompasses a number of stakeholders including the Ministry of Power, the Ministry of New & Renewable Energy, central electricity regulatory commission, state electricity regulatory commissions, state nodal Agencies, state renewable energy development agencies, research institutions, independent power producers, lenders (banks, NBFCs, multilateral /

bilateral financing institutions, private equity firms) and consumers among others. The following block diagram illustrates the relationship between various institutions which exists in Indian power sector.

**Figure 67: Existing institutional structure of Indian power sector**




*Source: CRIS analysis*

## 6.2.2 Legal and Regulatory Framework

### Electricity Act, 2003

As per the preamble of the Electricity Act 2003, it is "An Act to consolidate the laws relating to generation, transmission, distribution, trading and use of electricity and generally for taking measures conducive to development of electricity industry, promoting competition therein, protecting interest of consumers and supply of electricity to all areas, rationalization of electricity tariff, ensuring transparent policies regarding subsidies, promotion of efficient and environmentally benign policies, constitution of Central Electricity Authority, Regulatory Commissions and establishment of Appellate Tribunal and for matters connected therewith or incidental thereto."

Further, Electricity Act 2003 has the following provisions for the promotion and development of renewable energy sources in India:

- **Section 86(1)(e):** The State Electricity Regulatory Commission shall „promote cogeneration and **generation of electricity from renewable sources of energy** by providing suitable measures for connectivity with the grid and sale of electricity to any person, and also specify, **for purchase of electricity from such sources**, a percentage of the total consumption of electricity in the area of a distribution licensee".
- **Section 61(h):** The Appropriate Commission shall, subject to the provisions of the Act, specify the terms and conditions for the **determination of tariff**, and in doing so, shall be guided by the promotion of co-generation and **generation of electricity from renewable sources of energy**.

- **Section 86(1)(b):** The SERCs shall discharge the function **to regulate electricity purchase and procurement process of distribution licensees** including the price at which electricity shall be procured from the generating companies or licensees or from other sources through agreements for purchase of power for distribution and supply within the State.
- **Section 3(1):** The Central Government shall, from time to time, prepare **the National Electricity Policy and Tariff Policy**, in consultation with the State Governments and the Authority for development of the power systems based on **optimal utilization of resources** such as coal, natural gas, nuclear substances or materials, hydro and **renewable sources of energy**.
- **Section 66:** The Appropriate Commission shall endeavor to promote the development of a market (including trading) in power in such manner as may be specified and shall be guided by the National Electricity Policy referred in Section 3 in this regard.

## National Electricity Policy, 2005

The National Electricity Policy was notified by the Central Government in February 2005 as per the provisions of Section 3 of EA 2003. Clause 5.12 of National Electricity Policy outlines several conditions with respect to the promotion and harnessing of renewable energy sources. The salient features of the said provisions of NEP are as follows:

- **5.12.1** Non-conventional sources of energy being the most environment friendly, there is an urgent need to promote generation of electricity based on such sources of energy. For this purpose, efforts need to be made to **reduce the capital cost of projects based on non-conventional and renewable sources of energy**. Cost of energy can also be reduced by promoting competition within such projects. At the same time, **adequate promotional measures would also have to be taken for the development of technologies** and the sustained growth of these sources.
- **5.12.2** The Electricity Act 2003 provides that co-generation and generation of electricity from non-conventional sources would be promoted by the SERCs by providing suitable measures for connectivity with grid and sale of electricity to any person and also by specifying, for purchase of electricity from such sources, a percentage of the total consumption of electricity in the area of a distribution licensee. Such percentage for purchase of power from nonconventional sources should be made applicable for the tariffs to be determined by the SERCs at the earliest. Progressively, the share of electricity from non-conventional sources would need to be increased as prescribed by the state electricity regulatory commissions. Such purchase by distribution companies shall be through a competitive bidding process. Considering the fact that it will take some time before non-conventional technologies compete, in terms of cost, with conventional sources, the Commission may determine an appropriate differential in prices to promote these technologies.
- **5.12.3** Industries in which both process heat and electricity are needed are well suited for cogeneration of electricity. A significant potential for cogeneration exists in the country, particularly in the sugar industry. SERCs may promote arrangements between the co-generator and the concerned distribution licensee for purchase of surplus power from such plants. Cogeneration also needs to be encouraged in the overall interest of energy efficiency and grid stability.

## Tariff Policy, 2006

The National Electricity Policy was notified by the Central Government during January 2006 as per the provisions of Section 3 of EA 2003. The Tariff Policy has further elaborated the role of regulatory commissions, mechanism for promoting harnessing of renewable energy, timeframe for implementation etc. Clause 4 of the Tariff Policy addresses various aspects associated with promotion and harnessing of renewable energy sources. The salient features of the said provisions of Tariff Policy are as under:

- Pursuant to provisions of Section 86(1)(e) of the Act, the appropriate commission shall fix a minimum percentage for purchase of energy from such sources taking into account availability of such resources in the region and its impact on retail tariffs. Such percentage for purchase of energy should be made applicable for the tariffs to be determined by the SERCs latest by 1 April, 2006. It will take some time before non-conventional technologies can compete with conventional sources in terms of cost of electricity. Therefore, procurement by distribution companies shall be done at preferential tariffs determined by the appropriate commission.
- Such procurement by distribution licensees for future requirements shall be done, as far as possible, through a competitive bidding process under Section 63 of the Act within suppliers offering energy from same type of non-conventional sources. In the long-term, these technologies would need to compete with other sources in terms of full costs.
- The Central Commission should lay down guidelines within three months for pricing non-firm power, especially from non-conventional sources, to be followed in cases where such procurement is not through competitive bidding.

## National Action Plan on Climate Change, 2008

The National Action Plan on Climate Change (NAPCC) outlines a national strategy to enable the country to adapt the climate change mitigation plans for enhancing the ecological sustainability of overall development. The NAPCC recognizes the important role of renewable sources in sustainable development and prescribes the target share of renewables in the total power purchase mix to reach to 10% and 15% by 2015 and 2020, respectively. Key action plan of NAPCC is as follows:

- Focus on promoting understanding of climate change, adaptation and mitigation, energy efficiency and natural resource conservation. Mitigation comprises measures to reduce the emission of greenhouse gases by switching to renewable sources of energy.
- One of the 8 National Missions outlined in the NAPCC, is the National Solar Mission which lays the path of development of solar energy sector in India. The objective of the National Solar Mission is to significantly increase the share of solar energy in the total energy mix. It is aiming to increase the solar capacity to 20 GW by 2022.
- Adopt the Dynamic Minimum Renewable Purchase Standard (DMRPS or the Renewable Purchase Obligations specified for each distribution licensee). It suggests minimum consumption from renewable sources within country to be 5% starting 2009-10, which is to be increased by 1% every year for next 10 years, i.e., 15% consumption from renewable sources by 2020.

Hence, the NAPCC lays the foundation for the development of renewables in the country. Policies and incentives at the central & state level are relatively aligned with the above objectives, which are tools to achieve such ambitious targets. However, a certain degree of integrity and orientation in the overall policy and incentive framework for promotion of renewables is still required in the country to effectively achieve the 12th Plan and NAPCC targets.

## Renewable Purchase Obligations, 2010

As per the Electricity Act 2003, the SERCs have been empowered to specify a percentage of electricity to be procured by the obligated entities from renewable sources of energy. Most of the SERCs have issued orders/regulations specifying such percentages known as the „Renewable

Portfolio Standard" (RPS) or „Renewable Purchase Obligation" (RPO). The table below highlights the RPOs levied by various SERCs in their respective states.

**Table 43: RPOs for various Indian States**

| State | FY 2014-15 | | FY 2015-16 | | FY 2016-17 | |
|---|---|---|---|---|---|---|
| | Non-solar | Solar | Non-solar | Solar | Non-solar | Solar |
| **Andhra Pradesh** | 4.75% | 0.25% | 4.75% | 0.25% | 4.75% | 0.25% |
| **Assam** | 6.75% | 0.25% | - | - | - | - |
| **Arunachal Pradesh** | 6.80% | 0.20% | 6.80% | 0.20% | 6.80% | 0.20% |
| **Bihar** | 4.25% | 0.75% | - | - | - | - |
| **Chhattisgarh** | 6.00% | 0.75% | 6.25% | 1.00% | - | - |
| **Delhi** | 5.95% | 0.25% | 7.30% | 0.30% | 8.65% | 0.35% |
| **Gujarat** | 6.75% | 1.25% | 7.5% | 1.5% | 8.25% | 1.75% |
| **Haryana** | 3.00% | 0.25% | - | - | - | - |
| **Himachal Pradesh** | 10.00% | 0.25% | 11.25% | 0.25% | 12.25% | 0.25% |
| **Jammu & Kashmir** | 5.25% | 0.75% | 6.00% | 1.50% | 7.00% | 2.00% |
| **Jharkhand** | 3.00% | 1.00% | 3.00% | 1.00% | - | - |
| **Karnataka** | 10.00% | 0.25% | - | - | - | - |
| **Kerala** | 4.39% | 0.25% | - | - | - | - |
| **Madhya Pradesh** | 6.00% | 1.00% | - | - | - | - |
| **Maharashtra** | 8.50% | 0.50% | 8.50% | 0.50% | - | - |
| **Meghalaya** | 0.60% | 0.40% | 0.60% | 0.40% | 0.60% | 0.40% |
| **Odisha** | 6.25% | 0.25% | 6.70% | 0.30% | - | - |
| **Punjab** | 3.81% | 0.19% | 3.81% | 0.19% | 3.81% | 0.19% |
| **Rajasthan** | 7.50% | 1.50% | 8.20% | 2.00% | 8.90% | 2.50% |
| **Tamil Nadu** | 9.00% | 2.00% | - | - | - | - |
| **Tripura** | 1.45% | 1.05% | 1.65% | 1.10% | 1.85% | 1.15% |
| **Uttarakhand** | 7.00% | 0.075% | 8.00 | 0.10% | 9.00% | 0.30% |
| **Uttar Pradesh** | 5.00% | 1.00% | 5.00% | 1.00% | 5.00% | 1.00% |
| **West Bengal** | 4.35% | 0.15% | 4.80% | 0.20% | 5.25% | 0.25% |
| **Goa & Union Territories of India** | 2.60% | 0.40% | - | - | - | - |
| **Manipur** | 4.75% | 0.25% | - | - | - | - |
| **Mizoram** | 6.75% | 0.25% | - | - | - | - |
| **Nagaland** | 7.75% | 0.25% | - | - | - | - |

*Source: MNRE*

It can be seen from the table above that there are marked differences in RPOs. It is primarily due to the difference in renewable energy potential in those states. States possessing higher potential have higher RPOs.

### State-Level Policies

Apart from above mentioned Central level policies and regulations, various state governments have come up with policies to promote the development of the renewable energy sector in respective states. Some of these states have issued a single policy for all the renewable sources while others have issued renewable source specific policies based on the resources availability in respective states. The following table provides the list of various policies in Indian states.

**Table 44: State-Level renewable energy policies**

| State | Common | Wind | Small Hydro | Biomass | Bagasse | Solar |
|---|---|---|---|---|---|---|
| **Gujarat** | - | Yes | - | - | - | Yes |
| **Karnataka** | Yes | - | - | - | - | Yes |
| **Madhya Pradesh** | - | Yes | - | - | - | Yes |
| **Maharashtra** | Yes | - | Yes | - | - | - |
| **Rajasthan** | - | Yes | - | - | - | Yes |
| **Tamil Nadu** | - | - | - | - | - | Yes |
| **Andhra Pradesh** | - | Yes | - | - | - | Yes |
| **Haryana** | Yes | - | - | - | - | Yes |
| **Punjab** | Yes | - | - | - | - | - |
| **Himachal Pradesh** | - | - | Yes | - | - | - |
| **Uttarakhand** | Yes | - | Yes | - | - | - |

*Source: State Renewable Energy Development Authorities of respective State*

These state policies provide regulatory support in the form of state level incentives in addition to central incentives, single window clearances, dedicated nodal agencies, etc.

As can be seen from the table above, most of the states have come up with specific policies for promoting solar and wind energy in respective states. Gujarat and Rajasthan are pioneer states in introducing state-level policies for the solar and wind sector. As a result of these policies, they are leaders in installed renewable capacity in India and have been successful in driving private sector investments. Similarly, renewable resource specific policies are expected to promote growth in other technologies.

## 6.2.3 Incentives for Renewable Energy Projects

Coal-based thermal power projects form the backbone of power sector in India. Historically, electricity generation in India has been driven by these coal-based projects. Since energy generated from coal-based projects represents more than 70%[12] of the total electricity generation in India, all India average cost of generation remains significantly low as compared to cost of generation from non-conventional

[12] Source: annual report FY 12 of Central Electricity Authority

sources of energy. This makes it difficult for non-conventional energy resources to compete with conventional energy resources. Hence, supportive policy and regulatory framework needed to be developed for the development of non-conventional energy sources in the country. The Government of India has introduced various policy and regulatory initiatives to promote development in the renewable energy sector.

Key incentives offered by the central and state level governments to attract private sector investments in renewable sources are as follows:

- Renewable energy certificates (REC);
- Accelerated depreciation (AD);
- Generation based incentive (GBI);
- Preferential/feed-in tariffs (FIT);
- Other incentives:
    - Income tax holiday – 80IA benefits;
    - Duty & tax exemption / concessional duty for imports;

The following section deals with major incentives offered by the central/state governments and their impact on the development of the renewable energy sector.

## Renewable Energy Certificates

In India, some states such as Tamil Nadu, Gujarat and Rajasthan have abundant renewable energy potential as compared to other states. This signifies the importance of harnessing renewable power from resource-rich states. However, states procuring renewable power over and above their RPO targets have to bear the impact of comparatively expensive renewable energy. Hence, state-specific renewable energy potential restricts the development of renewable sources. In order to facilitate states with low renewable potential to comply with respective stipulated RPOs, the Government of India launched the Renewable Energy Certificates (REC) mechanism in December 2010.

The REC mechanism expands the market for renewable energy by broadening the availability and scope of power products available to the customers. The concept of RECs is based on separating the environmental or green power attribute of renewable energy generation from the underlying electrical energy. This creates two separate, though related products for sale by the renewable energy generator:

- Electricity as a commodity; and
- Renewable attributes (alternatively known as REC).

One unit of REC represents the renewable attributes of 1 MWh of renewable energy generation. Renewable attributes may be sold separately or combined with electricity at the point of sale by the generator. These RECs are valid for a period of 730 days from the date of issuance. The certificates are traded on the two power exchanges – Power Exchange India Limited (PXIL) and India Energy Exchange (IEX) - between the floor price and the forbearance price which is fixed by the CERC. The table below prsents the floor and forbearance price of RECs for the current control period.

**Table 45: Floor & Forbearance Price of RECs in India**

| Type of REC | Floor Price | Forbearance Price |
|---|---|---|
| Solar | Rs 9,300 | Rs 13,400 |
| Non-solar | Rs 1,500 | Rs 3,300 |

*Source: CERC*

## Accelerated Depreciation

Accelerated depreciation (AD) is a major fiscal incentive offered to the renewable sector. As per the concept of AD, the project owner is allowed to claim depreciation to the tune of 80% on the gross asset block as tax deductible expenditure during the first year of operation of project itself. Since projects under the AD scheme are financed on recourse basis/balance sheet financing; the project developer is able to avail maximum benefits in the form of tax savings. In other terms, the AD scheme enables a profit-making company to set off a part of its equity investment requirements in a renewable project against the tax savings available through it.

The AD scheme was withdrawn from the wind energy sector with effect from 1$^{st}$ April 2012. However, the same has been reinstated by the Central Government in FY 15 for the remaining period of the 12$^{th}$ Five Year Plan.

## Generation-Based Incentives

The GBI scheme was introduced by MNRE for grid-interactive wind power projects to attract investments from independent power producers (IPPs) and other large-scale project developers who are not able to avail of AD benefits. The scheme was initially introduced in June 2008 on a pilot basis and then launched in December 2009 for 4,000 MW projects to be commissioned during the 11$^{th}$ Five-Year Plan (FY 12). The scheme involved providing an incentive of Rs. 0.50 per unit of electricity generation to the generator through the Indian Renewable Energy Development Authority (IREDA). Further, the projects availing AD benefits were not eligible under the GBI scheme, much in accordance with the spirit of GBI.

Under the scheme, GBI was capped at Rs. 6.2 million/MW spread over a minimum and maximum of 4 and 10 years respectively resulting in an annual cap of Rs. 1.55 million/MW. Projects under the feed-in tariff mechanism were eligible for receiving GBI for electricity injection in the gird. However, the scheme was discontinued by the Government of India after FY 12.

The Government of India reinstated the GBI scheme during Budget 2013 and it was notified in September 2013. The Government of India has identified funds to the tune of Rs. 800 crore for the second phase of GBI scheme. As per the issued notification on reinstatement of GBI, the incentive level has been kept the same at Rs. 0.50/kWh, as was in the previous scheme, whereas the overall cap has been enhanced to Rs. 10 million/MW for all wind projects commissioned during the 12$^{th}$ Plan with a total capacity capacity of 15,000 MW.

Apart from wind, a GBI scheme was also announced for solar power projects. A total of 98 MW of solar power projects were identified by IREDA, for which a GBI of Rs. 12.41/kWh was provided by MNRE to the state distribution company on direct purchase of solar power from the project developers. This scheme was discontinued after discovery of low tariffs under competitive bidding carried out for solar power projects during JNNSM phase 1.

## Feed-in Tariffs

CERC determines generic the feed-in tariffs/preferential tariffs (FIT) for power generating companies owned or controlled by the Central Government using a cost plus approach to allow reasonable returns to the investor as per the underlying regulations. The SERCs determine FIT for renewable projects in respective states using a similar approach for projects which are proposed to be implemented during the specified period. This provides long-term guaranteed returns for the investors with a low risk profile. The following table summarizes the FIT determined for various renewable energy technologies across various states.

**Table 46: FIT of Renewable Energy Technologies in India (Rs. per Unit)**

| | Wind | Small Hydro | Biomass | Bagasse | Solar Photo Voltaic | Solar Thermal |
|---|---|---|---|---|---|---|
| **Gujarat** | 4.15 | - | 5.17 | 5.17 | 8.97 | 12.91 |
| **Karnataka** | 4.20 | 3.40 | - | - | 8.40 | 10.92 |
| **Madhya Pradesh** | 5.92 | 6.25 | 6.28 | 6.28 | 10.44 | 12.65 |
| **Maharashtra** | 3.92-5.70 | 4.33-5.06 | 6.27 | 6.27 | 7.95 | - |
| **Rajasthan** | 5.64-5.93 | - | - | - | 7.50 | 11.67 |
| **Tamil Nadu** | 3.51 | - | - | - | 7.01 | 11.03 |
| **Andhra Pradesh** | 4.70 | 2.60 | 3.86 | 3.86 | 17.91 | 15.31 |
| **Haryana** | 3.88-5.81 | - | 4.20-8.62 | 4.20-8.62 | 7.20-7.45 | 11.34 |

*Source: Tariff orders issued by SERCs*

In case of solar photo voltaic based power projects, the FITs announced by the respective SERCs are usually considered as benchmark prices for conducting reverse competitive bidding, as these projects are being awarded at prices discovered through bidding routes.

### Other Incentives

Further, the central and state-level governments provide incentives in the form of income tax holidays, exemptions, etc., to promote renewable energy capacity additions in the state. Some of these incentives are:

#### A. Income Tax Holiday – 80 IA Benefits

The Central Government has exempted all „other" infrastructure projects from paying corporate tax for a continuous period of 10 years within the first 15 years of commercial operation as per Section 80 IA of the Income Tax Act (IT Act). During this period, the project is liable to pay the Minimum Alternate Tax (MAT) only, and optimum usage of MAT credits available under the IT Act can be utilized for the lowest possible tax liability across the project life.

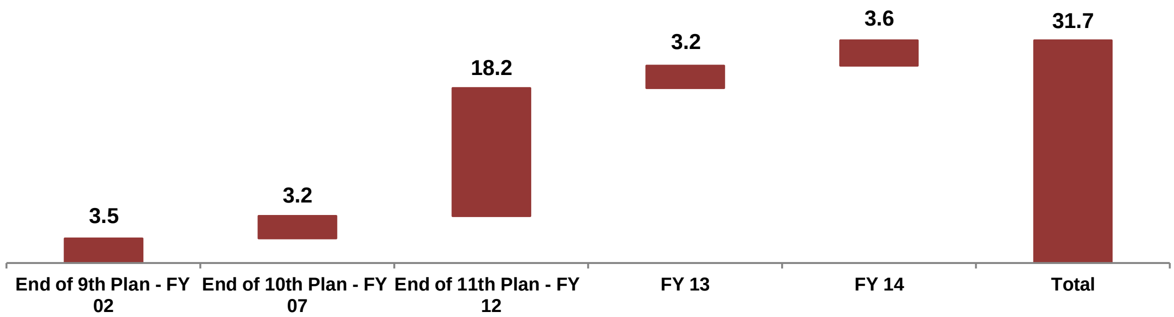
#### B. Duty & Tax Exemptions / Concessions

The Central Government also provides excise duty exemptions for the procurement of imported equipment to set up renewable-based projects in India. In addition, concessional custom duty is levied on the import of certain equipment for wind and solar projects whereas solar PV (thin film) modules are allowed to be imported at zero duty. Central Sale Tax to the tune of 2% is levied for inter-state sale of equipment whereas a few states exempt local purchases from Value Added Tax, to set up renewable projects.

## 6.2.4 Impact of Incentives on Renewable Capacity Additions

Promotional incentives provided by the central & state level governments have increased private sector participation in the renewable sector in the last decade. Further, renewable capacity has grown from 3.5 GW in FY 02 to 31.7 GW in FY 14[13]. The following bar graph highlights the growth in renewable energy capacity in India. As can be seen from the figure, the installed renewable capacity has grown at a CAGR of twenty two per cent (22%) in the last twelve (12) years.

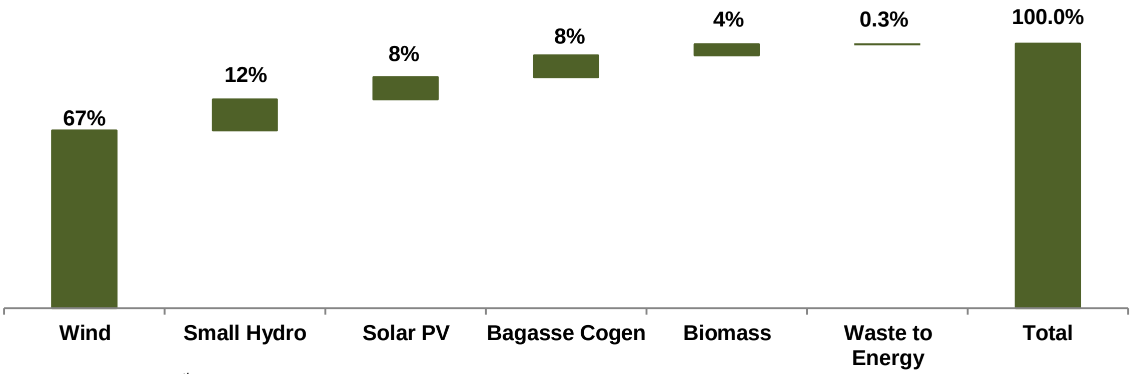
**Figure 68: Phase Wise Renewable Energy Capacity Addition in India (GW)**




*Source: MNRE, As on 31st March 2014*

Wind energy has been the fastest growing renewable sources in the last decade. In terms of installed capacity wind energy stands at 21,996 MW, followed by small hydro (3,856 MW), solar (2,765 MW), bagasse (2,689 MW), biomass (1,365 MW), and waste to energy (106 MW).

**Figure 69: Current Breakup of Installed Renewable Capacity (%)**

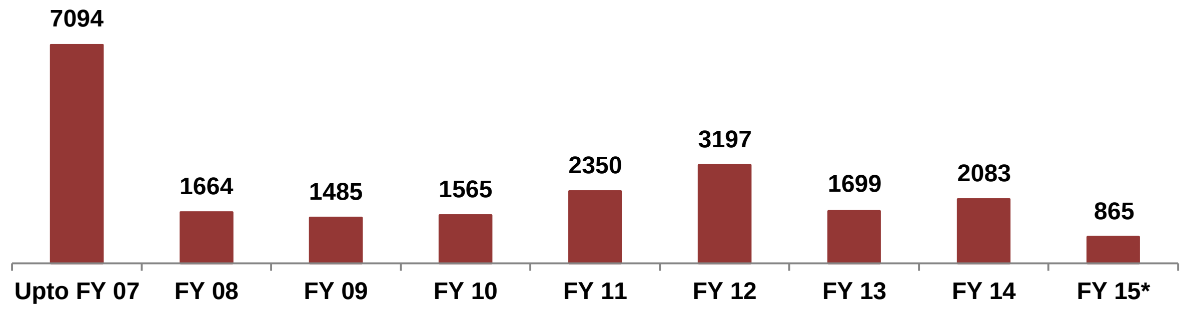



*Source: MNRE, As on 30th September 2014*

The growth of wind sector has been primarily fuelled by a combination of FIT and AD schemes in the initial years followed by REC and GBI schemes in the later years. As can be seen from the graph below, a substantial decrease in the wind capacity addition was observed during FY 13 after the discontinuation of D and GBI schemes.

[13] *As per MNRE, total installed renewable capacity in India as on 30th September 2014 = 32780.40 MW*

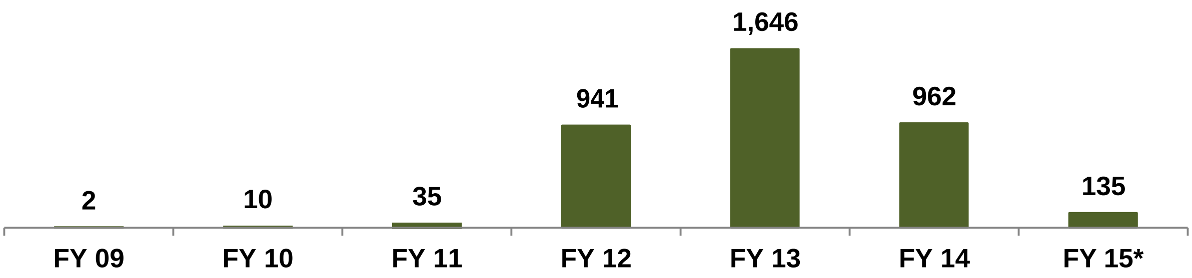
**Figure 70: Trend in Wind Capacity Additions (in MW)**




*Source: MNRE, As on 30th September 2014*

In solar sector, the capacity additions were promoted by FITs announced under JNNSM phase 1 and Gujarat solar policy during initial stages. Later on, with the fall in global prices of solar panels, major capacity additions took place through the competitive bidding route.

**Figure 71: Trend in Solar Capacity Additions (in MW)**



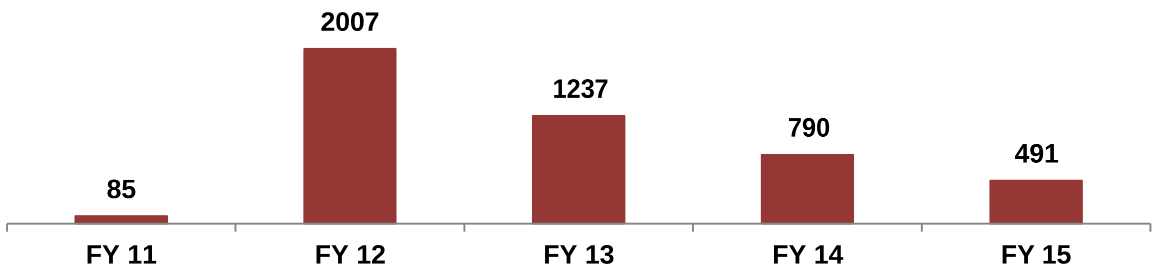

*Source: MNRE, As on 30th September 2014*

This section talks about the impact of key schemes on the development of the renewable energy sector in India.

## Impact of REC Scheme

As discussed above, the REC mechanism was launched with an aim to support states with low renewable energy potential in meeting their annual RPO targets. The scheme was well received by the project developers in its initial years as around 3.6 GW of renewable energy projects were installed under the REC mechanism between FY 11 and FY 13. The following graph showcases the capacity registered under the REC scheme in the last five years since its inception.

**Figure 72: Capacity Registered Under REC Mechanism (in MW)**

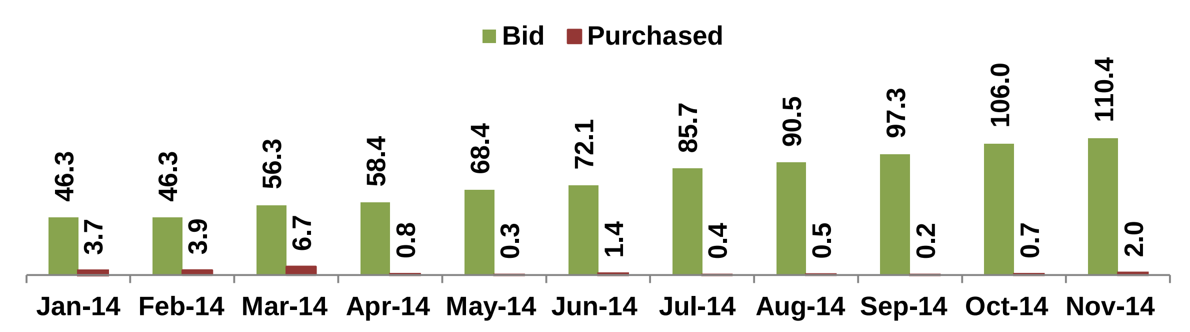



*Source: REC Registry, as on 1st December 2014*

However, the investor‟s interest in the REC scheme subdued in the last couple of years due to lack of demand of RECs in the market. As can be seen from the above figure, the capacity addition under the REC mechanism has come down from around 2GW in FY 12 to 0.79 GW in FY 14. This can be majorly attributed to the lack of strict enforcement of RPO targets by SERCs on the obligated entities especially power distribution utilities.

There has been a drastic fall in the demand of RECs as distribution utilities have not shown major interest in procuring green certificates for meeting RPO targets. This has led to piling up of unredeemed RECs to the tune of 11,426,646 unredeemed RECs as on 1st December 2014. The figure below shows the supply-demand analysis of the last 11 trading sessions at both exchanges.

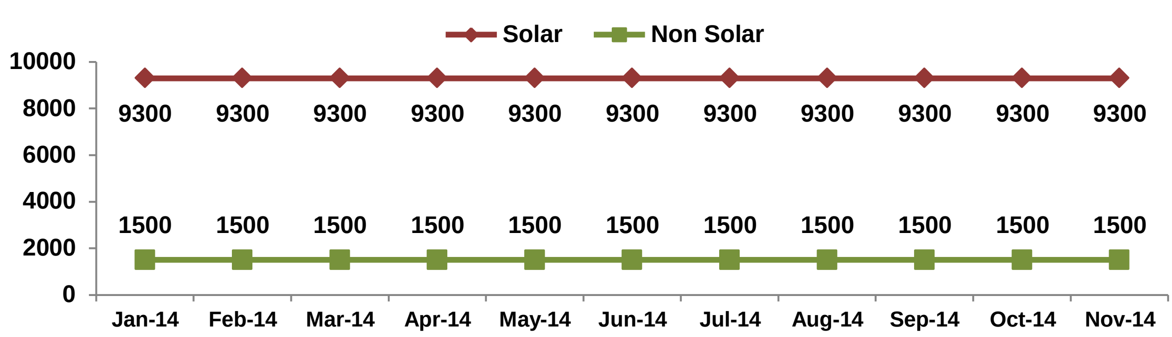
**Figure 73: Demand Supply Scenario of RECs (In Lakhs)**




*Source: REC Registry, as on 1st December 2014*

Further, absence of proper demand for RECs has clearly affected their clearance prices at the exchanges. The non-solar RECs have been trading at the floor price of Rs. 1,500 per REC during the past 11 trading sessions, whereas the clearance price of solar RECs has been ranging around Rs. 9,300 per REC during the same time. The figure below presents the trend followed by the REC prices on both exchanges.

**Figure 74: Trend for clearance price of non-solar REC (in Rupees per REC)**




*Source: REC Registry, as on 1st December 2014*

Hence, the fall in demand of RECs combined with the continuous increase in supply has led to a large number of unredeemed RECs for future trading sessions. The REC framework has not been able to match up to the expectations due to a number of operational and functional hurdles apart from the enforcement of RPO.

Since, the REC mechanism is very important for the overall development of the sector due to diversity in renewable potential in India, CERC has proposed draft amendments to REC guidelines to improve the overall framework. Finalization of proposed amendments combined with legal enforcement of

RPO through amendment in the Electricity Act is expected to give impetus to the REC mechanism and market in future.

### Impact of AD Scheme

The AD scheme has been one of the major contributors for the development of the renewable sector in general and wind energy sector in specific as AD has resulted in attracting sizeable private investments in the wind sector. As per MNRE, around 2,000 MW of the 3,100 MW wind capacity during FY 11-12 came up via the AD route. Before the discontinuation of AD benefit in FY 12, around 15,000 MW of wind power projects were implemented under the scheme in 1994-2012. AD being a tax-induced incentive was able to attract small-scale, medium-scale and captive investors in the renewable energy sector.

### Impact of GBI Scheme

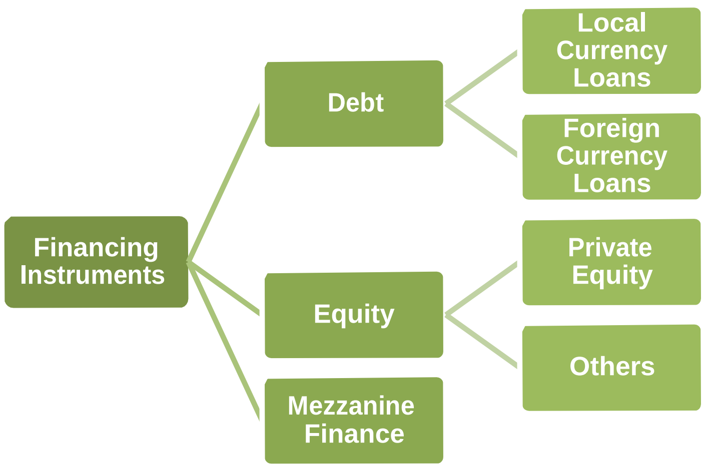
Unlike the AD scheme, the GBI scheme has not been in place for a very long period. A total of 2100 MW of wind projects were installed under the GBI scheme during Phase 1. Most of these projects were large-scale projects which were set up under the project finance route. GBI being a productivity-linked incentive was able to encourage investments in large-scale wind farms.

## 6.3 Sources of Renewable Energy Financing

In India, renewable energy projects are financed by various classes of financial institutions (FIs). These include but are not limited to commercial banks, non-banking financial institutions, private equity funds, and bilateral, and multilateral institutions. As can be assessed from the source of funds and risk expectations for specific projects; the return expectations chiefly depend on the cost of capital for each type of investor.

Renewable energy projects are characterized by relatively high initial investments which are followed by low variable costs in the subsequent years. Since, LCOE is impacted by high initial investment, higher financing costs in the initial years increase the overall LCOE for renewable energy projects. Hence, the cost of renewable energy in India is almost equal to its European counterpart despite the lower labour costs. The following figure showcases the various financing instruments available for renewable energy projects in India.

**Figure 75: Major Financing Instruments for Renewable Energy Projects**




*Source: CRIS Analysis*

This section deals with the various financing options available for renewable energy projects in India.

### 6.3.1 Debt Financing

Debt financing is the most favoured financing option for infrastructure projects in India. This is due to the fact that cost of raising debt capital is lower than the cost of equity; as rate of interest is cheaper than return expectations on equity. In this subsection, we will describe some common debt instruments available in India for financing renewable energy sources.

#### Local Currency Loans

Local currency loans are provided by various FIs for the development of infrastructure projects in India. These loans are provided under recourse as well as non-recourse route. Under the recourse financing (balance sheet financing) route, the borrower provides a guarantee / collateral for loan repayments to the lender from their company assets. The non-recourse financing (project financing) route, on the other hand, involves repayment from the profits of the project alone and no guarantees in the form of other assets are provided.

Local currency loans are provided by commercial banks (public & private sector) and NBFCs (government backed and private). The following table presents a snapshot of rupee term loan financiers in India.

**Table 47: Financers in Renewable Energy Sector in India (rupee term loan)**

| Type of Investor | Category | Total Registered in India | Active in Renewable Sector |
|---|---|---|---|
| **Commercial Banks** | Public Sector Banks | 26 | 09 |
| | Private Sector Banks | 30 | 06 |
| **Institutional Investors** | Insurance Funds | 24 | 11 |

*Source: CRIS Analysis*

As can be seen from the table above, a number of FIs are not involved in renewable energy financing in India. It leads to high cost of financing for renewable energy projects.

#### A. Commercial Banks

Commercial banks, both public and private sector banks, have been one of the major lenders to the power sector in India. Based on the project size, the funding is done by a single bank or a consortium of banks. The following table presents the key norms of financing of renewable energy projects through commercial banks.

**Table 48: Brief Profile of Commercial Bank Lending in Renewable energy Sector**

| | Public Sector Banks | Private Sector Banks |
|---|---|---|
| **Rate of Interest (%)** | 12% - 14% | 13% - 15% |
| **Loan Tenure (Years)** | 8 - 12 years | 5 - 10 years |
| **Share in Overall Project Cost (%)** | 60%-70% | 60%-70% |
| **Key Commercial Banks** | State Bank of India, Central Bank of India, Punjab National | Axis Bank, HDFC Bank, Yes Bank, IDFC Bank, ICICI |

| | Public Sector Banks | Private Sector Banks |
|---|---|---|
| | Bank, Canara Bank | Bank |

*Source: CRIS Analysis*

As can be seen from the table above, the interest rate charged by the local commercial banks is in the range of 12-15%, which leads to high cost of debt for the renewable energy projects in India. Further, commercial banks are not able to provide long-term loans due to asset liability mismatch as loan tenures of greater than 5 years account for 10%- 20% of the overall exposure for most of the commercial banks.

In India, commercial banks‟ credit flow to a particular sector depends on the banking and financial sector regulations and sector allocations. It has been found that regulatory bodies do not mandate lending to any sector as the credit decision ultimately lies with the lender who is exposed to the risk. Therefore, the sector exposure is a function of existing regulations as well as the banks internal policies and risk profile of the available projects. In most of the cases, renewable energy has been defined as part of the power sector, and since banks are approaching their lending limit for the power sector, they are often reluctant to fund RE projects.

### B. Non-Banking Financial Companies

Non-banking financial companies (NBFCs) such as IREDA, Power Finance Corporation (PFC), and L&T Infrastructure Finance etc. are also actively involved in funding renewable energy projects in India. These NBFCs are not bound by most of the banking policies and regulations applicable to commercial banks, such as the base rate limit and hence can lend at comparatively lower interest rates. However, it has been observed that their rate of interest is almost equivalent to that of commercial banks. The following table provides a brief profile of NBFCs in the Indian RE sector.

**Table 49: Brief Profile of NBFC Lending in RE Sector**

| | Public NBFCs | Private NBFCs |
|---|---|---|
| **Rate of Interest (%)** | 12% - 14% | 13% - 15% |
| **Loan Tenure (Years)** | 8 - 10 years | 10 - 15 years |
| **Key NBFCs** | IREDA, PFC | L&T Infrastructure Finance |

*Source: CRIS Analysis*

## Foreign Currency Loans

Nowadays, a number of RE projects in India are being financed by foreign currency loans. These loans are provided by multilateral / bilateral development banks, external commercial borrowings (ECB), Export Import financing, etc. Unlike, local currency loans, these loans are offered at lower interest rates with longer tenures and hence are well suited for Indian project developers. However, being in foreign currency, mainly USD / Euro, these loans are prone to exchange rate fluctuations and hence involve hedging costs, which are in the range of 4%-6% in the current scenario. The following table provides a snapshot of foreign currency loans being offered in India.

**Table 50: Brief Profile of Foreign Currency Lending in RE Sector**

| | ECB | Development Bank | EXIM Finance |
|---|---|---|---|
| **Rate of Interest (%)** | LIBOR + 3% / 5% | 3% - 6% | 3% - 6% |

| | ECB | Development Bank | EXIM Finance |
|---|---|---|---|
| **Loan Tenure (Years)** | 5 years / More than 5 years | 10-12 years | 10-15 years |
| **Key Lenders** | - | ADB, IFC, AFD, KFW, DEG | EXIM Bank of China, EXIM Bank of US |

*Source: CRIS Analysis*

There is a significant difference in the cost of debt from Indian and foreign banks. However, due to the hedging costs involved in foreign currency dealings, the overall cost of debt from foreign banks is around 2-3% lower than their domestic counterparts.

### Other Debt Financing Options

Apart from domestic and foreign currency loans, a number of products have been developed for financing RE projects. Some of the prevalent products are as follows:

#### *A. Supplier's Credit*

Under „supplier‟s credit‟, an equipment / product supplier extends credit to the procurer for the amount of equipment purchased by the procurer. This kind of arrangement is usually being practiced for imported equipment as supplier‟s credit enables the local procurer to gain access to cheaper foreign funds. The procurer usually issues a letter of credit to the supplier for the amount of loan for the said period. In India, a capital goods importer can avail a supplier‟s credit for a maximum tenure of 3 years and a revenue goods importer can avail a supplier‟s credit for a maximum tenure of 360 days.

#### *B. Bridge Financing*

Bridge financing/construction financing is a term used for financing availed for the construction period of the project. As per the risk profile of RE projects, the construction period is considered to be more risky than the operational period. Hence, the developer takes a construction loan for the construction period followed by:

- Permanent loan from another lender, which pays off the construction loan; or
- Construction loan converts into permanent loan at the end of the construction period

#### *C. Refinancing*

Under refinancing/take-out financing, the FI financing the infrastructure projects will have an arrangement with any financial institution for transferring to the latter outstanding loan in respect of such financing in their books on a pre-determined basis. Since, the risk involved in RE projects is reduced during the operational phase, investors are ready to refinance the existing loans with lower interest rates and longer tenure.

## 6.3.2 Equity Financing

In India, equity financing accounts for 30-40% of the total project cost as the lenders are not comfortable with more than 60-70% debt financing due to the inherent risks involved in RE projects. A number of equity investors range from private equity, venture capitalists, angel investors, etc. offer equity investments for power projects in India.

Depending upon the various projects related factors, such as project size, promoter history, technology being used, and policy risks, the equity investors aim for a risk-free return rate to the tune of 18-20% in India. Developmental banks including AFD-PROPARCO, kFW-DEG has equity arm and funds like GEEREF, Infraco Asia which make equity and quasi-equity transactions in all forms permitted by the company law and regulations: shareholder current accounts, convertible bonds/notes, participating loans, and subordinated loans.

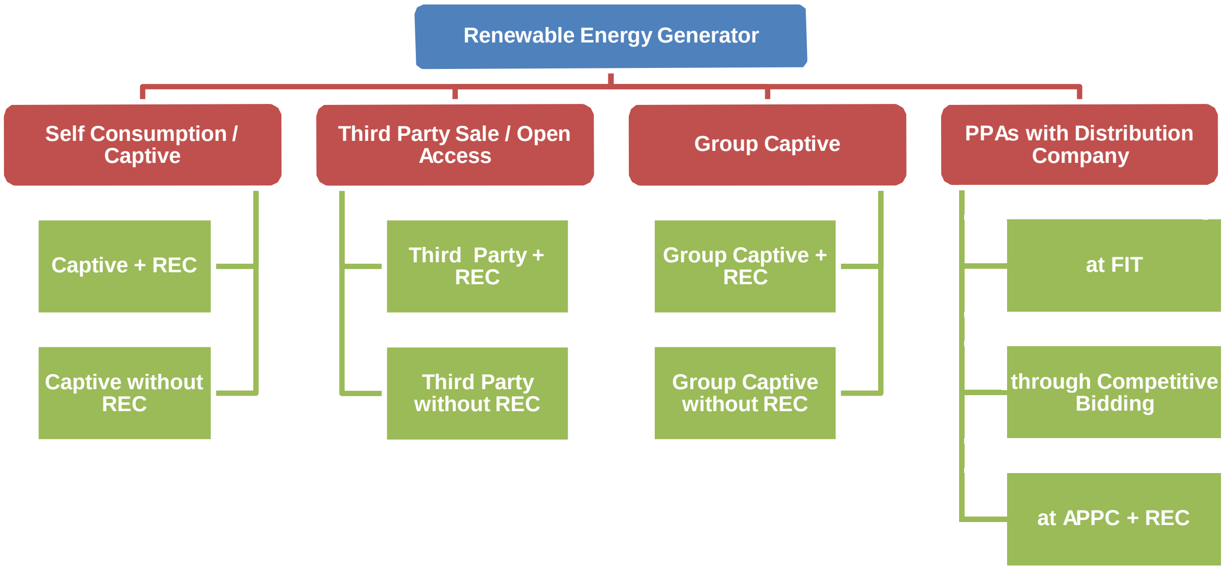
### 6.3.3 Mezzanine Financing

Mezzanine financing is a hybrid of debt and equity financing used for raising finance for expansion of existing companies. It is a loan given in the form of debt capital, which provides the lender with rights to convert to an ownership or equity interest in the company on non-repayment of loan. Mezzanine financing is has a high rate of interest in the range of 20% - 40% with a 3-5 year loan tenure.

## 6.4 Revenue Options for Renewable Projects

In India, a renewable energy generator can choose from various revenue models based upon the risk reward profile, commercials/charges, and ground situation/feasibility in each state. Sale option such as FITs is a low-risk-low-reward kind of option for the investors. Hence, in order to maximize returns, investors adopt more-risk-more-reward sale options such as third party/open access and group captive. The figure below exhibits various sale options available for the renewable generator.

**Figure 76 : Sale options available for RE generator**




*Source: CRIS Analysis*

The details of the above mentioned sale models are as follows:

### Captive / Self-Consumption + REC Model

In this model, an entity (captive generator) sets up a renewable project for self-consumption to meet its electricity demand. Being under the REC mechanism, the captive generator pays normal transmission and wheeling charges and losses specified by SERC. The captive user sells REC generated from the project, which provides additional revenue/income to the user. Such model is most common for bagasse-based cogeneration projects.

## Captive / Self-Consumption without REC Model

In this model, the captive user sets up a renewable project and consumes green attributes of electricity generated from its captive plant to meet its RPO. The user is also eligible for specified concessional transmission and wheeling charges and losses and banking facility under this option. Captive users are generally exempted from paying electricity duty and cross subsidy charge to the state distribution company/government in both the cases. This model is common for all renewable projects, especially for wind and solar-based projects.

## Third Party + REC Model

Under this model, the generator sells the electricity component to a third party consumer through open access and retains RECs, which are further traded on exchanges to earn revenue. The generator pays normal transmission and wheeling charges and losses specified by SERC. In addition, the generator has to bear the burden of expenses towards cross subsidy surcharge and electricity duty. All the above mentioned charges are levied on the third party consumer availing open access for renewable source and ultimately has to be paid by the generator so that the landed cost of electricity for the third party consumer remains less and competitive as compared to the grid rates.

This model is considered risky and is uncommon as third party transactions without a banking facility poses operational hurdles. However, considering the revenues from REC, the sale option provides reasonably worthy net realization to the generator.

## Third Party without REC Model

Under this model, the generator sells both electricity and green component to a third party consumer through open access. Similar to captive without REC, the generator is eligible for specified concessional transmission and wheeling charges and losses. However, the generator still has to bear the burden of expenses towards cross subsidy surcharge and electricity duty.

This model is prevalent for wind projects in some states. However, the net realization for the generator comes out to be lower than that in Third Party + REC due to high component of cross subsidy surcharge payable under this model with no other revenue source.

## Group Captive + REC Model

This sale model is a blend of captive and third party models with its own added advantages. Typically, in group captive, association of entities forms a group and invests a total of 26% common equity in renewable projects to consume the electricity component in proportion of the respective ownership. Balance equity is generally held by the generator. This model is identified under the Electricity Rules, 2005.

Being under REC, the generator has to pay normal transmission and wheeling charges and losses specified by SERC. However, as captive users are exempted from cross subsidy and electricity duty charges, the net realization from this model comes out to be significant with added revenues from the sale of REC. As of now, the group captive model is adopted mostly by wind generators due to an upcoming trend in solar projects.

## Group Captive without REC Model

Under this model, both electricity and green components are sold to group captive users. The generator is eligible for specified concessional transmission and wheeling charges and losses and banking facility. The net realization under this model is less than that in Group Captive + REC, but having a banking facility eases transaction between the group captive users. Similar risk and implementation hurdles exist for this model, however, is the most preferable among IPPs especially for wind these days which fits into their risk reward profile. Solar is still upcoming under this model.

## Sale to Distribution Company Model

### *A. At FIT*

A long-term PPA, generally for 20-25 years, is signed with the distribution company at tariff specified by the respective SERC based on the cost plus return approach. This is the least risky sale option in the Indian scenario as the PPA is signed with the state utility. However, only few states offer significant FIT, wherein net realization even comes more than models as discussed above. Hence, this model is preferred for states having implementation risks in other sale models; having reasonable retail tariff; and which offers FIT in line with CERC guidelines.

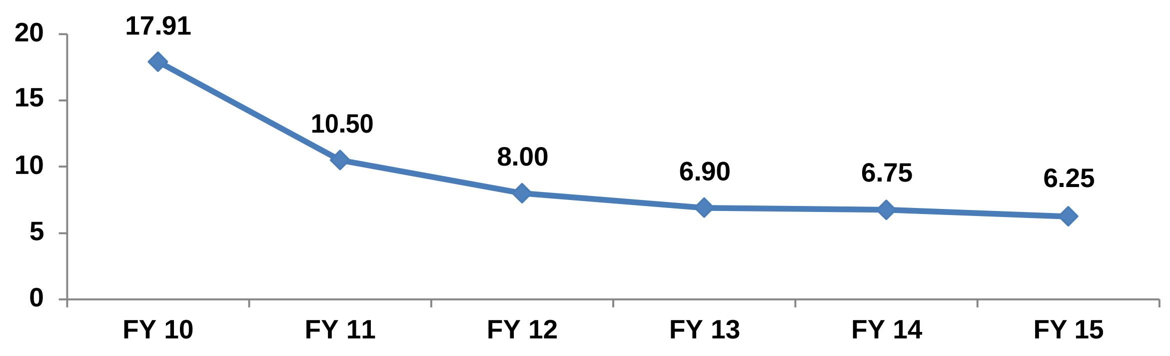
### *B. At APPC + REC*

As per this sale model, the generator sells electricity component to the distribution company at a rate equal to the average pooled purchase cost (APPC) of power of the distribution utility. Further, the generator gets RECs, which are sold in exchange to earn additional revenue. The APPC escalates at the rate of 3%-5% every year and is expected to escalate further at a much higher rate due to the increase in fuel prices. The risks under this option are demand and price uncertainty of REC including bankability of the projects. This model is gaining momentum for solar projects and is being adopted for wind projects in states with high APPC.

### *C. Through Competitive Bidding:*

As per this model, the generator sells power to the auctioneer (distribution utility/authorized agency) at a price discovered through the bidding process. In this model, the power procurer specifies an upper ceiling tariff and the project developer quotes per unit tariff within that limit. The developer with the lowest tariff bid is selected and awarded the project. In some cases, the auctioneer also provides viability gap funding to keep the power tariff as low as possible. This type of sale model is quite prevalent in India for solar project selection nowadays as it has resulted in a decline in the cost of solar power. The following graph showcases the trend in the price of solar power discovered in various bidding processes.

**Figure 77 : Trend in Cost of Solar PV Power**




*Source: CRIS Analysis*

However, there is a risk to compromise on quality aspects due to the focus on lowering the cost of power. Each of above revenue models offer specific advantages and disadvantages in line with the available opportunities and implementation issues in each state.

# 7. Strategy Roadmap

## 7.1 Introduction

The potential for economic growth, energy security, job creation, and global export inherent in wave and tidal energy technologies is considerable. India has a long coastline with estuaries and gulfs where tides are strong enough to move turbines for electrical power generation. The identified theoretical potential of tidal power is approximately 12 GW and that of wave power is approximately 41 GW. Furthermore, wave and tidal energy technologies have certain advantages over other energy sources:

- They provide an opportunity to generate energy at a wide range of locations throughout the Indian coastline.
- They produce energy at different times, and more consistently during the day than other renewable energy sources such as wind and solar. This will add to the overall stability of India‟s energy networks.
- The new technologies offer an attractive alternative in areas where the visual impact of electricity generation sources is a concern.
- Lastly, tidal and wave can leverage extra value by exploiting synergies with sectors such as offshore oil, gas, and offshore wind. Opportunities include using common components and sharing expertise on project development challenges.

The creation of tidal and wave energy industry could lead to a significant increase in jobs that is estimated to be in the range of 10-20 jobs/MW in coastal as well as in other regions as many equipment suppliers are not located in coastal areas. To deliver on the potential, this sector requires a long-term programme with industry and government working together on common issues. However, to make this effective, there is a need for certainty on both sides. The government needs to have certainty on cost and levels of deployment. The industry needs certainty around the wider policy framework, so that it can focus on securing finance, deploying the initial projects, and solving technical challenges.

There are uncertainties in the industry as to how some critical risks are managed. Risks can be best managed when shared between relevant parties who can effectively mitigate them, and to do this, a clear understanding of these risks is required. There are four significant risks that are currently impeding development in marine energy sector.

- **Financial risk** – There is a shortfall in upfront capital investment for technology development and pilot array demonstration, which is compounded by the current lack of long-term clarity on revenue supports. Both equity and debt are significant barriers in the development of marine energy technology based power projects.
- **Technology risk** – Uncertainties relating to survivability, reliability, and cost reduction potential are inherent in all new energy generation technologies, particularly in those designed for offshore operations in harsh conditions.
- **Project consenting risk** – Unknown interactions between devices and marine environments make it challenging for regulators and developers to assess and mitigate potential impacts.
- **Grid-related risk** – The best and most economical resources are frequently not located near accessible grid infrastructure, creating grave uncertainty over grid-connection dates in key areas.

Over the coming decade, the ability to reduce these risks will be the deciding factor when it comes to commercialising the wave and tidal energy sectors. For these sectors, it is clear that installing the first pilot tidal arrays will be a critical milestone.

First pilot array projects – consisting of three or more devices with a maximum installed capacity of 10 MW – will be the cornerstones of a successful market deployment strategy for India. They will, for the first time, prove the viability of generating electricity from more than one device, and thereby provides vital lessons, which will help developers target future innovations in array performance, reliability, and cost reduction. Successful demonstrations will not only pinpoint where further improvements are required; they will also boost investor confidence. This will stimulate investment into all stages of technology development and will help engage the supply chain. Successful electricity generation from the first arrays will also galvanise planning for future grid connection and development of efficient regulatory regimes.

## 7.2 Strategic Objectives – Goal Setting

| Milestone | Priorities | Goals |
|---|---|---|
| 2015 | ▪ Regulatory and policy framework for private sector participation in the development of tidal and wave energy in India<br>▪ Build Task Force comprising of scientists, policy makers, developers and financiers from interested stakeholders mentioned in the report and provide public funding for research and development in the sector. | ▪ Define target capacity addition by 2020 and 2030 and design feed-in-tariff and other fiscal and tax incentives for the development of the sector<br>▪ Collaborate, coordinate and leverage tidal and wave energy research<br>▪ Sign agreements with private sector to develop first ten pilot arrays |
| By 2020 | ▪ Demonstration and testing of First 10 pilot arrays<br>▪ Technology Innovation | ▪ Financial close on up to ten pilot arrays<br>▪ Technology innovation: reduce costs, increase reliability, increase yields |
| By 2030 | ▪ Innovation<br>▪ Supply chain engagement<br>▪ Accelerate cost reduction standardization and scale up | ▪ Commercial array installations (30 MW+) |

## 7.3 Strategic Plans – How To Get There?

Agreeing a common plan to de-risk wave and tidal technology development will be an essential step towards creating a new industrial sector in India. This roadmap will provide a clear account of the exact nature and level of support required for the wave and tidal energy sectors to fulfil its potential. Further, it will also indicate the levels of market push and market pull that will be needed to target key milestones. The government needs to ensure that the policy framework enables development through a coherent package of support provided by the government and other stakeholders.

### De-Risking Finance

Financing innovation and technology development at all technology readiness levels (TRL) is a key priority, with the goal of advancing several of the most promising early stage technologies. This will deliver the next pilot arrays for demonstration and ensure that the industry has no shortage of game-changers and second-generation solutions.

Wave and tidal energy companies need a suitably large and consistent pipeline of future projects to justify continued investment. They must see sustained commitment from nations to long-term stable mechanisms to support wave and tidal energy technologies, including technology push (capital grants) and market pull (market incentives, such as revenue support).

The pilot arrays should not be viewed as commercial projects, as they are a necessary R&D step following on from the demonstration of full-scale prototypes. Therefore, large capital grants, project equity loan guarantees, or soft loans will need to be combined with the available revenue support mechanisms to get these pilot arrays over the line. Deployment of the first pilot arrays will provide a clear view of wave and tidal energy route to the market. With practical experience and performance data under its belt, the industry can start to understand, quantify, and manage risks.

These pilot arrays will stimulate the appetite for investment in the whole sector, and will provide utilities with clear evidence that there is a market for wave and tidal energy. While revenue support mechanisms should be guaranteed for the lifetime of individual projects, they will need to be capped and time-bound to give a clear view of the duration and likely cost of the overall schemes.

### De-Risking Technology

Significant technology innovation is still required to deliver cost-effective, reliable, and high-performance solutions for wave and tidal energy generation.

Technology risk can be minimised by improving reliability and reducing the LCOE. The LCOE can be reduced via combination of capital cost cutting and improving yield, firstly at the level of the single device, and then through formation of array of multiple devices. This will require technology push, in the form of grants and capital investment in technology development, as well as market pull in the form of revenue support for scaling up deployments. Capital support is required for continued technology development at the research and design stage as well as for onshore and offshore testing and real-sea deployment of prototypes/pilot arrays. This twin-track „develop-and-deploy" approach will drive both innovation and early economies of scale.

Continued public sector support for research, innovation, and demonstration coupled with commitment from the industry will create a virtuous circle, in which increased reliability and cost reductions will trigger further investment. In the medium term, cost reduction will mean moving to standardised devices and components, integrating the supply chain, and mass-production of devices. However, this chain of events will depend on how the market being created. While the first pilot arrays will need large capital grants combined with revenue support, the industry will require clear and stable revenue support schemes to help it achieve significant economies of scale. Overall, closer cooperation between the public and private sectors will foster a common understanding of the most promising technologies and the highest priorities for innovation. This will automatically reduce risk and improve the strategic impact of public and private investments in wave and tidal energy technology innovation.

### De-Risking Project Consenting

Wave and tidal energy"s based projects are first-of-its-kind, which makes it challenging to evaluate the potential impacts that devices – and arrays of devices – could have on the marine environment. As a result, the planning and consenting process can be excessively expensive and time consuming, adding new layers of risk and uncertainty to wave and tidal energy projects. Disseminating best practice is the best way to mitigate this risk in the short term. Applying processes that have worked in one country to other areas seems an obvious win-win, but can be difficult to implement without the necessary political will. European countries are tackling consenting barriers for the nascent wave and tidal sectors by adopting a series of pragmatic actions: simplifying consenting procedures, such as marine planning, conducting a strategic environmental assessment (SEA), and developing a „one-stop-shop‟ for consenting. Regulators need to thoroughly examine the evidence base regarding consenting issues, including relevant evidence from other industries (e.g., the impacts from the laying and operation of power export cables from offshore wind farms), and revise consenting advice accordingly.

**De-Risking Grid**

The crux of the sector‟s grid issue is that high wave and tidal energy resource areas are in locations where the grid infrastructure availability is limited. Regulators are hesitant to facilitate sizable grid connections until it is certain that projects will connect and fully exploit them. While some companies are pursuing small-scale off-grid solutions, for several others, grid connection is causing substantial uncertainty, and will become an increasing concern as the industry moves past pilot arrays.

Grid planning and investment will require commitment and support from policy makers to ensure that key milestones for commercialising the entire sector are not held up by grid-connection problems.

### 7.3.1 De-Risk Financing Options

Wave and tidal energy, like established generation sources, has traditionally relied on government support, with some involvement from venture capital and private equity investors. The frontrunners in these sectors have started to emerge from the R&D phase, and private financing activity has picked up in response. In the last decade, a number of original equipment manufacturers (OEMs), utilities, and privately owned developers have acquired or invested in the leading small-medium enterprise technology developers.

In total, over €700 million in private investment has flowed into the industry in the last 8 to 10 years. This has yielded good results, and the market leaders are now close to securing finance for the small pilot arrays of tidal turbines. Predominantly on the wave power, companies have chosen to minimize the technology risk early by focusing on developing smaller-scale demonstrations for niche and/or intermediate markets, such as providing off-grid power to military installations, met masts, and navigational buoys. As a result of this progress, machines deployed in the last five years have generated over 10 GWh of electricity. Several other technologies have completed proof of concept with scale models in test tanks and ocean test sites across Europe.

In case of tidal and wave energy projects, arranging for equity financing would be a tough task due to the high risk perceptions associated with such projects. Similarly, debt funding needs to be arranged at a lower cost and for a longer tenure as compared to other renewable energy projects to bring down the costs. Hence, there is a need to look beyond conventional debt and equity financing mechanisms to fund such projects. Some of the innovative mechanisms / sources that can be utilised for wave and tidal energy projects are as follows:

- **Synthesized Products/ New Investors:** Pension funds, insurance companies, and sovereign funds should be allowed to invest in renewable energy projects. This would enable tidal and wave energy projects to have access to longer term investments.

- **Tax Free Bonds:** Renewable energy financing institutions such as IREDA should be allowed to raise capital from market via issuance of tax free bonds, for on-lending to renewable energy sector.
- **Exemption in Sovereign Guarantee Fee:** Currently guarantee fee is levied by Government of India on funds availed by different public sector entities from multilateral institutions such as ADB. This fee could be lowered for renewable energy projects and if possible tidal and wave energy projects should be exempted from such fees.
- **Improvement in Soft Loans Scheme:** Soft loans under IREDA NCEF Refinance scheme are available through IREDA at concessional rate. Uncertainty over such loans should be removed and payment timelines to IREDA should be improved so that the full allocation may be utilized during the financial year.

Further, equity investments sources such as angle investors, seed financing, venture capital financing, royalty financing, development capital financing (offered by PROPARCO) needs to be tapped for arranging equity at suitable rates.

Assuming that a good balance of capital grants and revenue support is made available, this industry could feasibly achieve financial close and obtain approval for the construction of 10 pilot arrays by 2020. Demonstrating technologies in pilot arrays will be a critical milestone for the whole industry. Regardless of technology type, array demonstration will maintain momentum and trigger further investment across all stages of development. However, securing that investment is proving to be a major barrier to reach financial close for the small pilot arrays.

### Market Push and Pull: Capital and Revenue Support

The UK has so far led the way in delivering financial support for technology push (public grants and private equity) and market pull mechanisms (feed in tariff, renewable obligations). This has already paid dividends, attracting significant inward investment in UK companies, skills, and test centres from across Europe and overseas. Ireland and France have now put capital and revenue support mechanisms in place to drive development, which is stimulating market activity in these countries. This new Irish and French support, together with the opportunity to secure grants from the European Commission‟s Horizon 2020 programme, is stimulating serious market interest outside the UK.

In May 2014, the French government received no less than seven competitive bids after it opened a call for tenders, offering capital and revenue support for up to four tidal pilot arrays in French waters. It remains to be seen whether the French equation for balancing market push and market pull will make it easier to get these projects to completion, but the high volume of bids clearly demonstrates that combining large upfront capital grants with enhanced revenue support is the key to stimulating significant interest in deploying pilot arrays.

The current experience with the first tidal pilot arrays (*being planned for construction in the UK*) shows that while enhanced revenue support is essential, the capital support packages currently available are not sufficient to get these projects approved for construction. Large capital grants, loan guarantees, or soft loans will also be needed to provide the level of market push required to get pilot arrays over the line.

**Table 51: Market Pull & Technology Push Programmes in Various Countries**

| Countries | Market Pull | Technology Push |
|---|---|---|
| **UK** | ▪ 20 year ROCs to be replaced by 15 year CFD in 2017 = EURO | ▪ MEAD, ETI, TSB, Crown Estate Scottish Government and Equity Investment (total |

| Countries | Market Pull | Technology Push |
|---|---|---|
| | 375/MWh until 2019 | Euro 120 m) |
| **France** | ▪ Approx. Euro 173/MWh EURO 200 m capital support for pilot projects | ▪ Established FEM (Euro 133 million for 10 years) De-risk technology upfront to ensure successful projects ADEME (Euro 40 million investing for future) |
| **Ireland** | ▪ Euro 260/MWh up to 30 MW from 2016 | ▪ SEAI Prototype Development Fund (Euro 10 million) RE RD&D programme (Euro 3.5 million) Ocean Energy Development Budget (EURO 26.3 million) |
| **Spain** | ▪ Moratorium suspending FIT for all renewables | ▪ BIMEP (EURO 20 million invested 2007-2014) PLOCAN (EURO 20 million for construction 2007-2014; EURO 16 million for O&M between 2015 and 2021) Ocean Lider (EURO 15 million for R&D support, 2009-2013) EVE (EURO 3 m Demonstration support 2014-15) |
| **Denmark** | ▪ Approx. EURO 80/MWh | ▪ Energinet.dk manages funds Energy Agreement (EURO 2.9 million) |
| **Portugal** | ▪ Scheme halted Previously Euro 260/MWh decreasing with capacity | ▪ FAI, QREN |

*Source: SI Ocean, 2014*

**Table 52: Proposed Pricing & Capital Support Mechanism**

| Project Scope and Scale | Market Mechanism | Description |
|---|---|---|
| **Small-Scale Development (Less Than 5 MW)** | FIT Testing Phase 1 | First rate proposed to be set for small-scale testing |
| | FIT Testing Phase 2 (Demonstration Stage) | Second rate significantly lower based on experience and technology development |
| | Capital support | Subsidies and grants to be provided for promoting small-scale developments |
| **Medium-Scale Development (5-10 MW)** | FIT Testing Phase 1 | First rate set at the rate established by CERC in near future for permitted testing and research facilities |
| | FIT Demonstration Phase 2 | Second rate set at the rate to be established by CERC for demonstration arrays |

| Project Scope and Scale | Market Mechanism | Description |
|---|---|---|
| **Commercial (30 MW+)** | Market for commercially competitive renewable electricity production | All projects applying for commercial licences must submit a plan to develop and deploy tidal and wave energy at a rate comparable to other sources of renewable energy. |
| | Viability gap funding | Viability gap funding to be provided to developers for lowering the cost of power supply |

### Key Recommendations

**Table 53: Key recommendations on de-risking financing options**

| Goal | Recommendation |
|---|---|
| Financial closure of ~10 pilot arrays by FY 20 starting from FY 15 | ▪ A dedicated national level policy needs to be prepared to focus on marine energy development.<br>▪ Dedicated nodal agencies should be specified for availing single window clearances and developing new technologies through research and development.<br>▪ Capital support in the form of grants and subsidies for demonstration and testing projects should be provided by the central as well as state level governments. |
| Remove financial and market-based blocks | ▪ Location and phase-wise feed-in tariffs should be provided.<br>▪ Stakeholder engagement consultation should be organized to sensitize lenders on marine energy development.<br>▪ Tax incentives in the form of tax holidays for initial 10 years.<br>▪ Excise and import duty exemptions for equipment & technology imported from leading countries<br>▪ Tax treaties with the leading countries<br>▪ Accelerated depreciation benefits is proposed for small scale projects and Generation based incentives for large scale projects<br>▪ Dedicated agency which will identify and mitigate the market related issues in development of tidal and wave power projects |

## 7.3.2 Deliver Reliable and Affordable Technology

### Status of Ocean Energy Technology

Wave and tidal technology developers have made significant progress in the recent years. The most advanced devices have undergone multiple design improvements and have sustained full-scale testing in operational conditions as stand-alone demonstration projects, which have generated over 10 GWh of electricity. Tidal technologies are expected to commercialize earlier than wave technologies, as evidenced by the number of tidal concepts that have managed to generate electricity during full-scale demonstration with devices of 1 MW or more. Tidal energy concepts present a greater convergence in design, with the majority of developers opting for horizontal-axis turbine concepts. Wave energy devices have not yet reached the same stage of development. Fewer concepts have undergone large-scale testing, and the sector presents a vast number of different concepts, with no clear convergence in design. This is partly due to the different characteristics of wave resources available at various water depths, which will ultimately require different technical solutions for power capture.

At this stage, significant innovation and further technology development will be crucial for delivering reliable and cost-effective wave and tidal technologies and for positioning these sectors as a major source of electricity supply for the future.

### Cost Reductions via Technology Development and Deployment

Delivering reliable and cost-effective technologies will be paramount to the ultimate commercial success of Europe‟s wave and tidal industry in the medium term. Commercial arrays will not reach the water without innovation that would lead to significant cost reductions, increased performance and reliability of successive iterations of prototypes and demonstrators. In the short term, demonstrating strong potential for cost reduction will send the right signals for further market support and investment. In the medium term, as the roll-out of larger scale tidal and wave energy arrays across multiple markets starts to happen, policy makers will need to see real and continued cost reductions to justify continued financial support. Reducing the LCOE of wave and tidal energy technologies will hinge on the progress on two fronts: (a) technology development at the research and design stage and (b) full-scale deployment of arrays to demonstrate the cost reduction from initial volume production. The second stage will be essential to prove that these technologies can work their way down the cost curve and achieve similar cost reduction in other more mature renewable energy technologies.

**Cost reduction will be driven by:**

- **Increased Performance: I**ncreasing energy yield and economic return by improving power capture, reliability, and survivability
- **Innovation:** Step changes – New devices or concepts, alongside new and improved components, sub-components, and materials for proven concepts
- **Experience:** Optimizing production, installation, and operations through learning by doing
- **Economies of Scale:** Volume manufacture, fixed maintenance costs spread over a larger number of devices (lower CAPEX and OPEX per device), and increasing the scale of converters (lower cost/capacity)
- **Cost Reduction:** Focusing on survivability, availability, and moving towards pilot arrays

The importance of improving the yield from wave and tidal energy devices as a factor in reducing cost cannot be overstated. To get there, the industry must specifically focus on improving survivability, reliability, and availability.

- **Survivability:** Wave and tidal energy converters must be able to survive both their expected operational loading, and the extreme loading seen during storm conditions. The ratio of extreme loads to operational loads is greater for wave energy than it is for tidal energy, so the challenge is steeper for wave energy converters.
- **Reliability and Availability:** Increasing reliability and minimizing downtime will improve the yield production and reduce the frequency of unplanned maintenance requirements. This can be achieved by improving the design, component selection, and better testing of the „mean time between failures as well as operational life expectancy of devices. It should also be noted that prioritizing onshore testing of survivability, component life expectancy, etc., can offer early wins in cost reduction – by helping to reduce the considerable cost of sea trials while also improving results.

### Innovation in Wave and Tidal Energy Technologies

Improving the existing devices, identifying game changers, and validating the performance and reliability of devices in real sea conditions, are essential. In the short term, technology should operate with a capacity factor of >25% and an availability factor of at least 75–85%. This will help to mitigate risk for potential investors. These figures should then be revised upwards, in line with technology development and operational experience.

Currently, there are many competing wave energy converter (WEC) designs. Improvements to power output, reliability, and survivability will be necessary before a consensus on the most promising design concepts can emerge. Innovation should encourage solutions optimized for two main locations – near-shore and offshore wave resources – and improving their efficiency and cost profile.

### Innovation in Components and Sub-Components

Failure of components and sub-components can have a huge impact on the LCOE of projects. Unscheduled maintenance can stop operations until a repair crew is sent out, sea conditions permitting. Optimizing the design of critical sub-systems will help minimize the impact of unplanned maintenance events. These sub-systems include:

- Foundations and moorings
- Support structures
- Power take-off systems (PTO)
- Power electronics
- Control systems
- Sensors

### Test and Demonstration Facilities

Setting testing standards, facilitating access, enhancing stakeholder coordination, developing standards and guidelines for testing, and demonstrating components, scale devices, full-scale devices, and the first arrays will accelerate technology progress for the entire industry. Clear standards and guidelines for testing protocols and evaluating results will also encourage investment from the supply chain.

### Enabling Wave and Tidal Energy Grid Integration

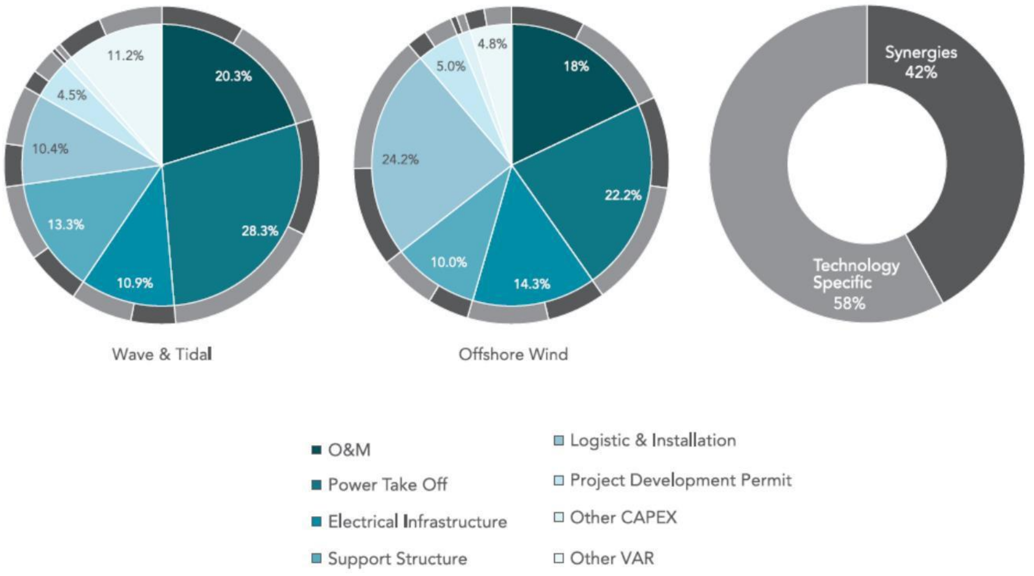
Without action, grid integration issues are likely to hinder the development of wave and tidal pilots and early arrays. Technical guidelines and standards for grid integration and connection need to be developed in coordination with other onshore and offshore energy sectors.

### Cost Reduction Potential till 2030

Technology innovation and learning by doing must be translated into a comprehensive cost-reduction pathway if wave and tidal energy technologies are to achieve cost competitiveness on commercial markets. Long-term cost reduction will be achieved by pure innovation, by standardizing processes and components during the design phase and by increasing competition. Learning rates could deliver a 12% cost reduction for every doubling of a repetitive activity. Increased deployment will increase experience and decrease risk. This will also have a positive impact on key elements of the LCOE, such as the cost of capital and insurance premiums, both of which are significant costs for CAPEX-intensive new technologies.

Cost reduction can also be delivered by developing Research & Development infrastructure to test marine technology with offshore wind. Both marine energy and offshore wind industries share synergies with regard to grid infrastructure, equipment, operations and maintenance procedures, as well as project development and permitting processes. Recent research carried out by SI Ocean indicates that offshore wind and wave and tidal projects could have component and project synergies of up to 40%. This represents another avenue for future cost reduction, and indicates the value of investigating opportunities for shared R&D into key components and processes with potential for application in both sectors.

**Figure 78: Synergies between wave and tidal energy and offshore wind**




*Source: JRC 2014, SI Ocean*

By 2030, more focussed R&D programmes, joint research, and industrial initiatives could deliver significant cost reductions. Collective efforts will need to focus on:

- Design consensus on off-the-shelf technologies
- Installation, operations and maintenance procedures (e.g., specialized station-keeping/cable-handling capability)
- Optimisation and standardisation of serial manufacturing of converters and materials

### Innovation in Installation, Operations and Maintenance system

Current installation costs for wave and tidal energy prototype projects are prohibitively high. Installation presently makes up 18% of the lifetime costs for a wave array and 27% of lifetime costs for a tidal array, considering both floating array of wave energy device and bottom-mounted tidal arrays. Developing best practice procedures for installation and operations and maintenance will help share knowledge and experience across the industry and drive cost reductions. This can only be done by deploying the first pilot arrays as soon as possible to cultivate cross-sector synergies in installation, maintenance, and retrieval of devices, thereby pinpointing opportunities for reducing CAPEX and OPEX.

In some circumstances, wave and tidal energy installations use offshore vessels from the oil and gas industry, at costs of between €120,000 and €180,000 per day. These vessels are neither cost-effective nor optimized for wave and tidal operating conditions, especially in the case of aggressive tidal flows. Optimized vessels will offer another potential source of cost reduction.

**Key Recommendations**

**Table 54: Key recommendations on delivery of reliable and affordable technology**

| Goal | Recommendations |
|---|---|
| Accelerate technology innovation aimed at reducing costs, improving reliability, and increasing yield, via research and design as well as deployment | ▪ Identify industry-wide targets for innovation and deliver a set of detailed pathways for key targets such as cost reduction<br>▪ Focus on collaborative projects (covering research, innovation and deployment) aimed at decreasing LCOE by improving:<br>□ Yield, reliability, availability and survivability of devices<br>□ Cost and performance of components, sub-components, and materials<br>□ Technical grid integration solutions<br>▪ Facilitate access to onshore and offshore testing facilities; devise testing standards, and prioritize testing of components, materials, and subcomponents, as well as full-scale devices |
| Deliver medium-term cost reductions through economies of scale by investing in development, innovation, and demonstration of pilot arrays | ▪ Develop tools to support array deployment<br>▪ Focus on standardization to reduce costs by developing „off-the-shelf" devices, components, and sub-components<br>▪ Share best practice from installation and O&M experience across the industry |
| Involve the supply chain and incentivize its innovation potential | ▪ Promote knowledge and technology transfer from other offshore industries such as oil & gas or offshore wind<br>▪ Identify and develop common specifications for standard components that will be required by several developers |

## 7.3.3 Develop Regulations and Consenting Regime for Project Development

Streamlining consenting processes and developing focused environmental monitoring protocols will ensure that early project developers receive consent in a timely manner, thereby reducing costs and delays. Understanding potential impacts will not only reduce costs and delays but also ensure that future arrays are located sensitively with regard to environmental impacts and key maritime stakeholder interests. Reducing uncertainty over the potential impacts of wave and tidal energy projects will require sustained coordination and collaboration between regulators, environmental advisors, stakeholders, developers, and researchers. Some of the best practices adopted in the world are as follows.

### 7.3.3.1 Strategic and Environmental Planning Programme

The government holds the responsibility for shaping the regulatory framework. Direction on maritime spatial planning (MSP), stakeholder consultations, and strategic environmental assessments (SEA) can help overcome potential conflicts of interest. Existing regulatory regimes and institutions familiar with guidelines for traditional maritime users (oil & gas, shipping, fishing, etc.) can work on developing planning guidelines for project developers on wave and tidal installations.

### Maritime Spatial Planning: Integrated Planning for All Stakeholders

Spatial planning is needed to maximize the benefits derived from India‟s seas without compromising on their ability to continue to provide benefits for generations to come. Factoring in wave and tidal energy installations should be considered as a short- to medium-term priority. India should prioritize the introduction of comprehensive spatial planning, with clear guidelines on selecting appropriate areas for wave and tidal energy projects taking into consideration the environmental impacts, other stakeholder interests, and economic production potential. With this backing, developers can maintain and build upon the current high levels of public support.

### Stakeholder Engagement and Consultation Process

Consultation is an integral part of the project development process. It is best started early and carried out frequently, with enough time to allow concerns to be resolved. Public exhibitions, meetings, and documentation are key parts of this process. Tidal and wave energy is lacking public awareness, as it is a very nascent industry. A public awareness campaign will be useful. It may provide similar benefits as was enjoyed by the wind industry in its early days. Successful stakeholder engagement will be essential for delivering early projects and increasing public acceptance of wave and tidal power projects.

### Strategic Environmental Assessments (SEA)

SEA answers to the questions such as how do tidal power devices and the supporting infrastructure interacts with the environment and how does the environment affect the devices and infrastructure?

Like any electrical generating facility, a tidal/wave power plant will affect the environment in which it is installed and operates. A number of environmental assessment studies have been assessing the potential impacts of wave and tidal energy. By undertaking SEAs, the government, regulators, and the investors/developers will be better informed about suitable locations for, and potential impacts of, wave and tidal power deployment.

### 7.3.3.2 Streamlining Consenting and Environmental Procedures

Proactive countries with a clear commitment to these sectors have already introduced many simplifications to consenting and environmental procedures to support wave and tidal energy deployments, including:

- Proposed Tailored and „fit-for-purpose‟ licensing processes
- „One-stop shops‟ to streamline and accelerate consenting
- Flexible consenting
- Data gathering proportional to the size of the project and the relative environmental impact
- Data sharing between sites and technologies where applicable

### Key Recommendations

**Table 55: Key recommendations for development of regulations and consenting regime**

| Goal | Recommendation |
|---|---|

| Goal | Recommendation |
|---|---|
| Allow for integration of wave and tidal energy in long-term planning and with existing ocean users | ▪ Finalize the implementation of maritime spatial planning and strategic environmental assessment directives<br>▪ Disseminate best practices for successful stakeholder engagement, including regulators, project developers, and other industries |
| Streamline and accelerate the consenting processes by removing excessive administrative and cost burdens | ▪ Generalize the use of "one-stop shops" for project consenting<br>▪ Ensure reasonable requirements for data collection to keep costs and delays in check<br>▪ Allow for flexibility in project consenting – survey, deploy, monitor<br>▪ Ensure that environmental monitoring data can be used as evidence for other projects and technologies |

### 7.3.4 Remove Grid Barriers to Wave and Tidal Energy Projects

#### Grid Issues Affecting Wave & Tidal Energy Industry

Grid poses a costly and difficult infrastructure challenge for wave and tidal energy projects today. Relatively few sites in India have the right mix of resources, reasonably sheltered waters nearby, infrastructure to support deployment and O&M, and grid access. While tidal energy resources are concentrated in a relatively small number of sites with medium to high flow velocities. These areas are often far from significant grid connections and are unable to integrate wave and tidal energy electricity into the grid.

The cost of grid upgrades is high. In some cases, upgrade costs can be equivalent to the total capital costs of the early arrays to be connected (for hundreds of megawatt capacity). The burden of underwriting grid upgrades in some countries falls directly upon the projects wishing to connect. Further to this, high connection charges and use-of-system charges are making early wave and tidal energy deployments unfeasible in many of the best sites. The up-front costs for developing and grid-connecting wave and tidal energy projects pose significant risk, as projects may not have received consent or have finalized the site design before they are required to spend significant amounts on development and even larger amounts to secure grid connections. These costs can potentially cripple wave and tidal energy projects.

On the other side, regulators are hesitant to facilitate grid connections and upgrades until it is certain that the industry can connect to them on time and fully utilize them at scale. This is causing substantial investor uncertainty in the industry.

#### Key Recommendations

**Table 56: Key recommendations on removing grid barriers**

| Goal | Recommendation |
|---|---|
| Explore innovative ways to reduce prohibitive costs and delays for connecting early stage projects | ▪ Use public funding to reduce the weight of grid connection costs for small and early projects<br>▪ Identify ways to provide network operators with challenges and potential solutions in connecting |

| Goal | Recommendation |
|---|---|
| | successive stages of wave and tidal projects |
| Extend the grid to reach the wave and tidal energy resource rather than constraining ocean projects to grid-connected areas | ▪ Promote grid extensions and interconnections between neighbouring countries<br>▪ Integrate wave and tidal energy into short- and long-term grid planning |

### 7.3.5 Proposed Action Plan

**Table 57: Proposed Action Plan**

| Year | Research | Market Development | Regulatory System Development |
|---|---|---|---|
| **2015-16** | ▪ Establish a „Task Force"/Forum for R&D in tidal and wave energy<br>▪ Study environmental effects of tidal and wave power<br>▪ Facilitate access to onshore and offshore testing facilities, devise testing standards, and prioritize testing of components, materials, and subcomponents, as well as full-scale devices | ▪ FIT, Capital support and other market incentives for tidal and wave energy<br>▪ Begin work on small demonstration sites and marine electricity integration studies | ▪ Marine energy legislation - Dedicated national level policy needs to be prepared to focus on marine energy development.<br>▪ Establish strategic environmental assessment programmes<br>▪ Streamline and accelerate the consenting processes by removing excessive administrative and cost burdens |
| **2020** | Ongoing technical and environmental research | ▪ Deployment of 10 tidal and device arrays using a stage approach at commercial site<br>▪ Testing and demonstration of wave arrays | ▪ Integrate wave and tidal energy into short- and long-term grid planning |
| **Post 2020** | **Commercially competitive tidal barrage and in-stream technology.** | | |

# Annexure – 1

The Ministries/Department which will be involved in the processes of granting clearances for Marine energy projects with the nature of clearance required are as follows. Besides, there may be additional agencies or additional clearances from any of these agencies which may be specified later.

**Central Government Agencies**

- Ministry of Environment & Forest – EIA, CRZ clearance
- Ministry of Defence – Security clearance
- Ministry of Shipping – Clearances for projects near Major Ports
- Ministry of Petroleum and Natural Gas – Clearance to operate outside oil and gas exploration zones
- Ministry of Civil Aviation – Aviation Safety
- Department of Telecom – Clearance for operating outside subsea Cable zones
- Geology and Mining Department – Seabed and related environment issues
- Department of Animal Husbandry, Dairying and Fisheries – No impact on fishing grounds
- Ministry of Home Affairs – Declaring wave and tidal energy exploitation zone.
- Department of Space – Clearances relating to satellite launching stations

**State Government Agencies**

- State Government – Clearance for working under Coastal Zone Management Plans
- State Maritime Boards - Clearances for projects near Minor Ports
- State Electricity Utility or a similar Designated Agency.
- State Renewable Development Agency
- District Commissioner – Land use permission, public hearing for environmental clearance.
- Any other stakeholder from the State Government.

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