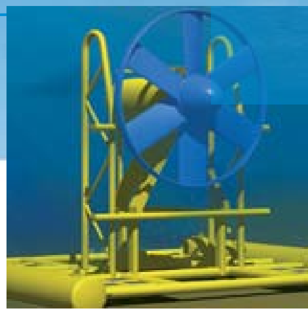

Roadmap for renewable marine energy

ADEME

French Environment & Energy Management Agency

Sommaire

Foreword

This roadmap elaborates a vision of renewable marine energy that is built upon consultation with a group of experts drawn from industry, public research bodies and the French Environment and Energy Management Agency (ADEME).

In the course of these working sessions the experts expressed their opinions intuitu personae. The views outlined in this roadmap are not to be assimilated with the official positions of the corporations or research organisations to which the members of the group belong.

List of experts consulted

Type of organisation	Name	Affiliation
Private corporations	Frédéric Le Lidec Jacques Ruer Cyrille Abonnel Jean François Dhédin Jean Yves Grandidier Jean Luc Achard	DCNS SAIPEM EDF EDF VALOREM LEGI
Research organisations	Alain Clément Hakim Mouslim Michel Paillard Marc Bœuf	Ecole Centrale Nantes Ecole Centrale Nantes IFREMER Pôle Mer Bretagne
Competitive clusters	Patrick Poupon Vincent Guénard	Pôle Mer Bretagne ADEME
Agencies	Samy Guyet Jean-Louis Bal Michel Gioria Bernard Gindroz Régis Le Bars	ADEME ADEME ADEME ADEME ADEME

> 1. The objectives of the call for expressions of interest for marine energy under the Research Demonstrator Fund

The Research Demonstrator Fund has set three objectives for marine energy:

- develop economically viable technologies to improve the capacity to tap the strong hydrokinetic, wave power and thermal energy potential available along French coastlines (mainland France and overseas departments and communities),
- a representative set of pilot projects will provide the basis for systems evaluation and optimisation of connection and compatibility with existing electrical power grids, and help to make these solutions socially acceptable,
- real-life operation of these pilot projects will make it possible to quantify the environmental impact of energy production on the ocean bed (erosion, unequal sediment distribution, etc.) and on other users of ocean resources (also taking into account maritime security and compatibility with national defence concerns) and support proposals for compensatory measures as the case may be. Further investigations will be carried out regarding machines grouped in energy "farms".

> 2. Marine energy and today's energy context

Binding European objectives for final consumption of renewable energy in 2020

In its Climate Plan (23 January 2008) the European Commission reiterated the importance of electricity from renewable resources, setting an overall objective of 20% renewable energy in final energy consumption (all uses combined– electricity, heat and fuels) by 2020, for the 27 Member countries. In December 2008 the European Council reached a historic agreement on an energy and climate change package, to be finalised in 2009 by the European Parliament.

In this context France's objective is to achieve 23% of renewable energy in final energy consumption by 2020. According to the report drawn up by the Renewable Energy operational committee of the Grenelle environmental conference, to reach the goal of 20% by 2020 the share of renewable energy in final energy consumption would have increase by 20 million tonnes-oil-equivalent (Mtoe). A roadmap was therefore drawn up to accompany the development of renewable energies, incorporating quantitative objectives for mature or nearly mature power generation technologies. French energy legislation (*Programme fixant les orientations de la politique énergétique*, or POPE law) calls for cutting greenhouse gas emissions by three-quarters by 2050; this will necessitate even more ambitious development of renewable energy, particularly electricity. At the same time it is likely that certain objectives set for 2010 by the pluriannual investment programme decided in 2006 will not be met. To reach this emissions reduction target, France must develop technologies that are technically, economically, socially and environmentally viable, especially if the country is to fulfil its ambition to be a leader in the field of renewable energy.[1]

How can marine energy contribute to renewable energy in France?

A maritime nation, France possesses significant marine energy resources. French jurisdiction covers well over 10 million square kilometres of sea and ocean waters, with an exploitable energy potential that is one of the largest in the world.

France also has a broad network of actors, scientific and industrial laboratories and research centres with the qualifications and expertise for the characterisation of marine energy resources and for the viable integration (technical, economic, social and environmental) of the technologies required to exploit them.

Rational integration with maritime activities

Along with technical obstacles, the social and environmental consequences of intensive exploitation of the multiple forms of marine energy are not yet well characterised.

Research is needed to ensure their development in a sustainable fashion. Sustainable exploitation of the oceans and coordinated management of the French coastline must be implemented, taking into consideration the concerns of all stakeholders, for this area of power generation to make a significant contribution to the energy mix in the future.

In this respect development of marine energy must be coordinated with future schemes for managing European Natura 2000 @ Sea sites (29 zones currently identified as Special Protection Areas in France and 47 Sites of Community Importance).[2]

1 - Speech given by the French president at the summary session presenting conclusions of the Grenelle environmental conference, Elysée Palace, 25 October 2007.

2 - Beginning in the first quarter 2009 and to be completed by end 2012.

> 3. Marine energy and industrial sectors

Several countries hope to develop a national industry

With the exception of the proven technology of offshore wind turbines, marine energy represents a significant resource that is not yet exploited on an industrial scale. With the development of the first prototypes of significant size it seems possible that industrial activity could start up by 2015, bringing economically profitable equipment to market in context of rising demand and depletion of fossil fuels.

Over the long term marine energy technology could follow a trajectory of falling costs similar to those observed for wind power and photovoltaics over the last two decades.

At the international level

A number of European countries, including Denmark, Ireland, Portugal, Spain, Sweden and the United Kingdom, are ready to enter the technological race for marine energy, along with other world players such as Canada, Japan, New Zealand and the United States.

The United Kingdom

Today the United Kingdom appears to have the most thoroughly structured sectoral strategy, via financial support (over €200 million committed from 1999 to 2008[3]) for an activity chain ranging from fundamental research (the academic programme SuperGen Marine) and "acceleration" schemes for the development of balance-of-system components (Carbon Trust Marine Energy Accelerator) to pre-commercial deployment (Marine Renewable Deployment Fund), with the overall aim of supporting innovative scientific and industrial initiatives upstream of large-scale commercial operations.

The Energy Technologies Institute, a public-private partnership, was created in the UK in late 2007. The institute funds a pre-competitive research programme on marine energy that, among others, relies on the testing capacity that has been acquired over the past few years, notably at the European Marine Energy Centre (EMEC) which has contracted with several developers of wave power and marine current turbines for testing at sea.

Ireland

There is much to be learned from the example of Ireland, which presents a very interesting approach. In 2006 Ireland adopted a strategy that comprises four phases, for two objectives:

1. add marine energy to Ireland's renewable energy portfolio,
2. develop a marine energy sector in the economy.

In the first phase (2005–2007) an offshore testing site for ¼ scale wave energy devices was constructed, and funding allotted to researchers and technology developers.

The activities of phase 1 are being pursued in phase 2 (2008 – 2010), with support for demonstration of pre-commercial prototype units, and preparation of a grid-connected test site. The third phase (2011–2015) will include pre-commercial testing of small groups of devices over a period of several years, and the final phase (2016 onwards) is expected to be devoted to developing commercial strategies for wave energy technologies.

A government White paper states the foremost objective in figures: 75 MW by 2012 and 500 MW in 2020. As far as funding goes, in 2008 the government allocated €26 million over three years to achieve the following goals:

- set up and operate a marine energy development unit within Sustainable Energy Ireland,
- establish wave and hydraulic energy resources and testing sites,
- rehabilitate a national wave test basin,
- institute a purchase mechanism for marine-generated electricity,
- create a fund to support industrial research and prototype development.

France has the means to build a national industrial sector

France has exceptional industrial experience and feedback from the tidal energy barrier and power plant in the Rance estuary that began operating in 1966, and remains to this day the world's largest tidal energy plant. Testing of a prototype in the Odet estuary near Quimper (Brittany) is beginning to provide information on tidal energy turbine technology, and feedback on offshore wind turbines will soon be forthcoming from another experiment, with the construction of the first line from the Veulette-sur-mer wind farm.

France can build on the recognised capabilities of its engineering firms specialised in marine installations and its industrialist companies, manufacturers of power generation equipment and offshore construction companies. Research organisations and laboratories in the country also have the skills and expertise to foster the development of a marine energy value chain.

3 - Renewable Advisory Board, January 2008, "Marine renewables: current status and implications for R&D funding and the Marine Renewables Development Fund", Renewable Energy Board (2007) 0182, URN 08/566.

… if it gets organised

To attain this objective a firm political determination is necessary, backed by strong implication of key actors in technology research, development and demonstration and with the acceptance of other users of marine and coastal resources. The relative lack of success of the call for tenders for offshore wind turbines in 2004 underscores the importance of this implication and the need to make these projects more socially and environmentally acceptable. In these conditions France could assume a leading role and prepare to achieve its long-term energy objectives.

In this regard the IPANEMA approach allows a broad range of stakeholders to exchange their views and together define a possible future framework for the deployment of marine energy in mainland France as well as in its most outlying territories, in particular by enabling consultation with all users of maritime resources.

This roadmap does not claim to anticipate the outcome of the IPANEMA approach; instead it outlines in general terms the issues that can guide thinking on technological subjects.

> 4. Ocean energy

The oceans are rich in energy streams that can be exploited in various ways: marine current energy, tidal energy, wave energy, offshore wind energy, ocean thermal energy, marine biomass, osmotic energy.

Estimating potential exploitable resources

The figures compiled here correspond to technically exploitable potential energy available for different production chains. By "technically exploitable" we mean energy that is practically extractable at a reasonable cost, for example on a par with the current cost price for a kWh of wind-generated electricity. We also assume that socially acceptable installations can be built at all the sites that have been identified as technically and economically promising.

One of the preponderant limiting factors for all production chains is the cost of the underwater electrical cable linking installations to the grid, roughly €0.5 million per km for the power generating capacities in question). If technological advances bring down this cost or if a breakthrough is made in electricity storage (hydrogen, batteries, compressed air, etc.) technically exploitable sites would not be restricted to a zone within roughly 20 km of the coast as is the case today. For example sea swell energy would be accessible, deepwater wind power could be developed using floating installations, and major ocean currents could be tapped by marine current turbines.

In this case marine energy systems would undoubtedly be more readily accepted, because they would cause less visible obstruction, but they would also have to be extremely sturdy, to virtually eliminate on-site maintenance. Generally speaking the technically exploitable potential could shift by one order of magnitude, for all production chains.

Types of technology

Depending on the form of energy, there are several families of technologies that present different types of bottlenecks. One way of presenting the technological bottlenecks is to describe the functional system groups: energy conversion system, support or anchoring structure, control systems, electrical connection, site intervention (installation and maintenance). Certain bottlenecks are found in specific production chains, as described below; others are common to all chains and are described in the following section.

Technological bottlenecks

The development of marine energy technologies proceeds in phases. The first phases validate a concept by systems modelling, using the appropriate digital simulation tools. The initial validation phase serves as a preliminary sizing step to prepare for reduced-scale experimentation in a wave basin. Power curves can be extrapolated and system performance calculated from experimental data.

Concept validation is followed by engineering stages. This phase furnishes a detailed economic estimation of costs for a prototype device, and by extrapolation gives an indication of the cost price for production from a full-scale commercial device. An economic model for the system is determined at this stage. The anticipated performance of the technological concept conditions the economic viability of the project.

A demonstration of technical feasibility is necessary for this development process by stages. The estimated production cost price must be reasonable, compared to the current cost of other forms of renewable energy, to support economic viability beyond the technological development phase. To achieve this viability the developers of new marine systems face some common problems in the economic process. Production costs must be estimated with respect to the maturity and technical potential of each supply chain.

All these technological bottlenecks call for in-depth work to optimise the system components for each concept from an economic perspective.

The technological bottlenecks can be categorised by functional group.

Mechanical conception and manufacturing

The mechanical design must take extreme environmental conditions into account, including wind, waves, current and detrimental physiochemical effects due to salinity, etc.

- Manufacture and assembly of large marine structures.
- Use of alternative materials (concrete, composite) for durable and economical housings.

Electrical design

- Anchoring and electricity transmission cables between the structure and the sea floor that can tolerate movement of the structure and hydrodynamic forces.
- Electrical connection systems for use in a marine environment and/or underwater when systems are put into place or disconnected to be towed into port.
- Rotating connectors for floaters set into the wind and/or current.

Installation in the marine environment

- Accessibility and simplified manoeuvrability for structures weighing several hundred tonnes (depending on available logistical options).
- Towing and mooring procedures.
- Installation and assembly of functional units in the marine environment.

Anchoring

As a general rule no universal anchoring technique can be prescribed, because different sea bed conditions require different techniques. Depending on project conditions one technique may be more economical than another.

Regardless of the technique, anchoring systems must be designed with high security margins to meet standards applicable to offshore structures that must resist stresses under extreme conditions. Installation and dismantling must be simple to hold down costs.

The following points should be noted, depending on the type of anchoring system:

- conventional ship anchoring systems that penetrate the sea floor resist only stresses that are essentially horizontal and uni-directional. They are fouled by traction and do not withstand vertical stresses;
- gravitational anchoring must take Archimedes' principle into account. The mass of material used depends on its density;
- the diameter and depth of piles driven into the seabed (drilled or hammered) may vary considerably depending on the nature of the floor.

Control devices for machines or groups of machines

- Mechanical, hydraulic and electrical controllers to optimise energy production and limit mechanical stresses that may be destructive.
- Coordination, coupling and balancing output in groups of several turbines.
- Adjustment of generator response to recover as much energy as possible.
- Adjustment of load factors for electrical components and improved efficiency.

Energy converters
- Sizing of energy storage capacity and current levelling
- Performance of turbines and electrical components in seawater
- Subsystem fatigue and analysis of needs for redundancy.

Electrical connection
- Distance to high-voltage grid for large-capacity offshore farms (>100MW).
  Present situation:
  long distance = prohibitive costs = not economically viable
- Waterproof high-voltage connection/disconnection technologies to protect the power grid and systems
- Dynamic cable performance and coupling of mechanical forces
- Optimised electrical performance and sizing of grid connection for groups of turbines
- Limitation of transmission line losses.

Operations and maintenance
- Fully secured access for maintenance visits
- Resistance under extreme conditions

Dismantling
All structures installed offshore must be dismantled at the end of the project's service life and the site returned as nearly as possible to its initial pre-project state. It is worth noting that installation of these systems can have beneficial effects for ecosystem reconstitution.

Non-technological bottlenecks

In addition to the technological bottlenecks mentioned above, for these value chains to be successfully deployed in France other obstacles – social, regulatory or economic in nature – must be overcome.

It must not be forgotten that regardless of the value chain and technology chosen, the utilisation and operation of marine energy parks must be accepted by the people and users who draw work or leisure from the sea.

Marine energy must confront several challenges:

- economic viability: while the inevitable rise in energy prices linked to fossil fuels, and the falling cost of renewable forms of energy thanks to advances in knowledge, mass production and technological progress makes the economic viability of marine energy seem more and more likely in the long term, it remains nonetheless that as for all innovative sectors profitability will come only after a period of costly R&D investment that carries risks;
- social acceptability: Marine energy technologies must show that they can be optimally integrated into the environment of their natural surroundings and that not only do they not disturb human activities, they can even benefit local, regional and national economies. As with other forms of renewable energy, they will inevitably encounter opposition from some groups;
- security: It must be demonstrated that marine energy systems and installation procedures fully guarantee the safety and security of people and equipment during all phases, from construction, operation and maintenance to dismantling;
- regulations: The deployment of offshore energy production systems using new techniques is today confronted with a set of inconsistent regulatory texts that were not written with this situation in mind, and which contain variously contradictions, omissions and blockages. This non-technological obstacle recurs across several renewable energy supply chains; the first attempts to set up offshore projects have shown that the road will be particularly rocky for marine energy.

> 5. Marine current and tidal energy

Marine current energy (hydrokinetics) is derived from the kinetic energy of water masses set in movement by currents provoked by gravitational fluctuations due to the Earth's movement in relation to the sun and the moon. This mechanical energy is converted by turbines into electrical energy or hydraulic energy transported to land.

The speed and times of tidal currents depend on the lunar cycle, with the advantage that they can be calculated long in advance. The predictable nature of this cyclical intermittence is a major advantage of this form of marine energy. Furthermore, in the English Channel the progression of the tidal surge as it propagates through the channel theoretically makes it possible to ensure a relatively constant power output from generating equipment installed at the many productive points in this zone.

The electrical power that can be extracted from moving water masses is proportional to the cube of the current speed, at the surface where the system is implanted, and to the density of the water. Underwater horizontal-axis marine current turbines can be seen as submerged windmills. Although marine currents have a velocity that is just one-quarter or one-fifth of wind speeds, the power output of a marine turbine is much greater than that of a wind turbine of the same size because the fluid medium is much denser (sea water is 800 times denser than air). Consequently tidal current turbines can be much smaller than land-based wind turbines, making them suitable for energy extraction in shallow sea waters.

Potential exploitable resources

Potentially productive zones are those where current speeds are greater than 1 ms^{-1} and water depth is at least 20 m so that the turbine can generate sufficient power.

Marine energy resources in Europe are found principally in the United Kingdom (75%, half of which is located off Scotland) and in France (20%, off the coasts of Brittany and Normandy).

In these regions the tidal current is amplified by the shape of the coastline in certain special areas (narrows, seabed formations, bathymetric features). Hydrohélix Energies estimates that the coasts of mainland France have a potential natural resource of more than 6 GW, with several sites in Brittany and Normandy where current velocities are particularly high. EDF estimates that the technically exploitable resource is between 5 and 14 TWh/year, corresponding to 2.5 to 3.5 GW of installed capacity.[4] Certain sites have specific potential, with narrows, headlands, gullets, etc. where current speed increases. For example: Raz Blanchard, Fromveur, Raz de Sein, Héaux de Bréhat, Raz de Barfleur; and overseas: the effects of points, passages, etc.

Technologies

A great many concepts have emerged for the energy exploitation of marine and tidal currents: the European Marine Energy Centre (EMEC) counted over 50 such concepts in 2008, whereas the ocean energy systems group of the International Energy Agency (IEA-OES) had noted only five in 2003.

The types of conversion devices that can be used to exploit hydrokinetic energy can be classified in three categories:

- horizontal-axis axial flow turbines,
- vertical-axis cross-flow turbines (horizontal-axis turbines are also possible),
- "paddle-wheel" horizontal-axis surface turbines,
- "singular" conversion devices that do not use turbines. These include:
  - > hydrofoil devices mounted on an articulated arm and that oscillate vertically under the combined effects of lift and drag,
  - > horizontal cylinders placed on mobile supports (VIVACE project): in a certain speed range a Bénard-Von Karman vortex path is created. When a vortex is shed, a non-symmetrical flow is formed around the cylinder, modifying the pressure distribution and creating a periodic lift on the cylinder, causing vibrations. These vibrations can be amplified and their mechanical energy converted to electricity if the shedding frequency is close to the frequency of the vibrating structure.

4 - Depending on the length of annual operating periods.

Each turbine class can be further divided into the following subcategories:

- turbines equipped with shrouds (concentrators) or not Shrouds are subdivided into symmetrical Venturi-effect ducts that are suited to the ebb and flow of tides, or asymmetrical (divergent) diffusers that yield a larger increase in output but are restricted to use in one-way river currents, unless they are mounted on a rotating base;
- stand-alone turbines, or turbines sharing a common support structure, in which case they may also share a single power generator.

Various support structures and methods are used to anchor converters in productive areas, depending on whether the device emerges at the surface or not, and on the nature of the underlying soil bed:

- mounted on piles driven into the seabed,
- tripod or four-footed structures that penetrate the seabed,
- gravitational solutions,
- floating anchored structures.

The type of combination of converter and support structure – monobloc assembly or not – will determine the methods to be used for installation and maintenance operations at sea.

Technological bottlenecks

The technological bottlenecks that affect current energy systems are not specific to this technology, and are described in section 4.3.

International benchmarks

In late 2008 the European Marine Energy Centre (EMEC) established a list of close to 50 wave energy conversion projects.

The systems in the most advanced stage of development are horizontal-axis turbines. The most notable of these projects are:

- the commercial SeaGen project undertaken by Marine Current Turbines Ltd : 1.2 MW turbine connected to the Northern Ireland grid since 2008;
- Verdant Power (United States): 6 tidal current turbines installed in the East River (New York City);
- OpenHydro (Ireland): 250 kW prototype installed at EMEC since 2006, grid connected since 2008, and a 1 MW prototype to be installed in the Bay of Fundy, in partnership with Cherubini Group and Nova Scotia Power;
- Hammerfest Strom (Norway): a 300 kW prototype initially installed in 2003 and reinstalled in 2009 after a verification phase;
- Tocardo (Netherlands): a 45 kW prototype installed in 2008 and a planned 10 MW installation on floating supports in the North Sea.

Several projects involving horizontal-axis turbines equipped with concentrators are underway:

- Lunar Energy: Rotech turbine for a projected 8 MW farm in Wales;
- Clean Current Power (Canada): a 45 kW prototype is being tested prior to a commercial project in the Bay of Fundy;
- Atlantis Resource Corporation (Australia): Nereus turbine, 150 kW prototype connected to grid since 2008 will be presented to EMEC (partnership with Statkraft).

Cross-flow turbine projects are rarer:

- Ponte Di Archimede (Italy) installed a floating turbine Kobold in the Strait of Messina in 2002;
- New Energy Corporation (Canada) with a 25 kW prototype of the Encurrent turbine;
- Ocean Renewables Power Company (United States) is developing a 32 kW demonstration of the OCGen system in the Bay of Fundy.

Hydrofoil projects are in less advanced stages of development: a prototype of the BioStream system has been set up by Bio Power Systems in the Bass straits (Australia).

The preceding section summarises marine current energy demonstration projects, the number of which is likely to rise, given the number of concepts studied and the decisions made in certain countries to develop this production chain (notably the UK and the USA).

> 6. Tidal energy

Tidal energy exploits the energy potential derived from the difference in level between two water masses.

Potential exploitable resources

The World Energy Council estimates the global potential of tidal energy, for "conventional single-reservoir" sites, at 380 TWh/year for 160 GW capacity. Tidal Electric Ltd estimates this potential to be 6 000 MW in the United Kingdom, and 2 000 MW in France for exploitation of tidal energy via artificial lagoons.

Technologies

The exploitation of tidal energy is based on the principle of two basins of water at different levels. The energy extracted is the potential energy represented by the difference between the two water masses. Typically the upper basin is filled at high tide, and the lower basin emptied at low tide. Enhanced cycles including a pumping phase have been devised to improve overall production, as well as systems using three basins.

Tidal energy converters that generate electricity can be located on the coast (barriers) or at sea (artificial lagoons).

International benchmarks

Barriers

At present there are only three tidal energy plants in operation in the world, for a total installed capacity of 265 MW.
The La Rance power plant is by the far the largest of the three with a capacity of 240 MW and annual output of 550 GWh.

The other plants are in Canada (20 MW) and in China (5 MW). In early 2008 the British government initiated a feasibility study for a vast tidal energy plant in the Severn estuary. A first list of 10 projects (barriers and lagoons coupled with tidal generating plants) was published in July 2008. The feasibility study evaluates project costs and benefits, was well as their environmental impact.

Artificial lagoons

Artificial lagoon projects are being studied for several sites in Wales: a 5 km^2 lagoon in Swansea Bay in the Severn estuary feeding 24 2.5 MW turbines for a total capacity of 60 MW; in Rhyl (432 MW) and at the Yalu site located 1 km off the coast of China (300 MW).

Technological bottlenecks

Tidal energy technology is a mature technology, for both land-based plants and artificial lagoons. The main obstacles to their development are investment costs and environmental impacts.

> 7. Wave energy

Waves and swell are generated by the interaction of wind and the water's surface. The size of the wave formed by this transfer of energy is determined by wind speed and direction, and the distance over which the wind acts, called fetch.

Waves that travel over long distances form swell, and are modified by bathymetric features that can concentrate or dissipate wave energy, and by oceanic or tidal currents.

Waves can potentially supply a sustainable energy resource that can be converted to electrical energy. Energy conversion devices have been developed to exploit wave energy in both shallow and deep waters.

Potential exploitable resources

The World Energy Council estimates that with a technically exploitable potential of 1 400 TWh/year wave energy could cover 10% of global energy demand for electricity.[5] The technically exploitable potential in mainland France can be estimated to be at least 10% of the total theoretical resource (400 TWh/year), or 40 TWh/year that could be produced by 10 to 15 GW of generating capacity located mainly on the Atlantic seaboard. In overseas departments and communities, strong potential has been identified in Reunion, Polynesia, New Caledonia and locally in Martinique and Guadeloupe.

The energy dissipated by sea swell amounts to more than 22 000 TWh per year globally, representing close to one quarter of the planet's energy needs.

This energy is generally expressed in kW per metre of wave front (kW/m). On the French Atlantic seaboard the average energy transmitted by waves has been estimated at 45 kW per metre at the crest line, corresponding to a total annual gross energy potential of 417 TWh, very close to total annual electricity consumption in France (476 TWh in 2006). These are of course orders of magnitude, that simply show that just a fraction of the energy resource could make a significant contribution to the energy mix in the future.

Technologies under development

Wave energy converters are categorised by conversion process. There are four groups that can be described as follows:

- oscillating water columns: systems that compress air by oscillation of water in a chamber that communicates with the ocean. The pressurised air mechanically drives a turbine. These systems can be either floating installations or fixed on the coastline;
- overtopping devices: waves break on artificial ramps and the water is collected in raised reservoirs before flowing through low-head turbines. These systems can be either floating installations or fixed on the coastline;
- floater (pitching) devices: these systems are made up of one or several floating bodies set in movement by waves. The movement of the floaters drives energy converter machines, either hydraulic or direct electrical generators. Several different concepts exist;
- seabed systems: these systems are attached to the sea floor and use the oscillation of water caused by waves throughout the entire water column. The underwater fluid kinetic motion moves various kinds of devices (swinging panels, submerged buoys, bodies that change shape, etc.) that in turn drive energy conversion systems which can be electric or hydraulic, using sea water under pressure to transport energy to land.

In these four system families, mechanical energy is converted to electricity using hydraulic systems or direct power generation. The energy conversion can occur onboard if the system is located at sea, or on land if the installation is close to the coastline, and in the case of hydraulic conversion.

The impacts of the system structures must be carefully evaluated for all types of systems. Current work on these technologies favours applications that are far from the shore, insofar as is technically and economically feasible, because installations that are distant from the shore have a lesser impact and are more readily integrated into future energy farms in the public maritime domain and beyond. Furthermore, in addition to reducing the potential conflicts between stakeholders, waves contain more energy far out at sea than in the coastal zone.

5 - Global electricity demand is roughly 14 000 TWh/year.

International benchmarks

In late 2008 the European Marine Energy Centre (EMEC) established a list of nearly 100 wave energy conversion projects. The most advanced projects under development are in demonstration or pre-commercial phases. Below we list the most mature projects, by system type.

Shore-based oscillating water columns (OWC) are in quite advanced stages of pre-commercial systems:

- a 400 kW installation on the Island of Pico in the Azores has been in activity since 2000;
- more recently the 100 kW WaveGen Limpet project (a Voith Seimens partnership) on the Island of Islay in Scotland started up in July 2008.

Demonstration projects of the OWC technology are also planned: Iberdrola Renovables 296 kW EVE project cofinanced by the European Community (Spain); 500 kW Oceanlinx project (Australia); joint Tractebel/Petrobras 50 kW Pécem project (Brazil). Floating OWC systems are being tested with the Ocean Energy Ltd project in Galway Bay, Ireland. The British firm Orecon has developed a buoy-shaped converter, the 1.5 MW Wave Hub off the coast of Cornwall. The Wave Hub is a testing centre equipped with a 20 MW electrical cable to test pre-commercial versions of wave energy systems. This centre will start operations in 2011.

Overtopping devices are few in number. The Danish project Wave Dragon successfully completed its demonstration phase, and has been grid-connected since 2005. Several units will be installed in Wales (a 7 MW project in 2010, to reach 10 units in 2015 for a 70 MW project) and in Portugal in 2011 (10 units totalling 50 MW).

The articulated floaters of the Danish Wave Star system installed at the end of a breakwater has been in demonstration since 2006. After this successful operation a test section for a planned 500 kW system has been deployed at sea on the Horns Rev sandbank near a wind farm.

Other floater systems installed at sea are in various stages of maturity:

- Tussa Kraft: three 40 kW units are connected to the grid (Norway, project in partnership with Vattenfall);
- EMEC: a 3 MW farm composed of four Pelamis units is planned (in partnership with Scottish Power Renewables);
- a 2.25 MW farm with three Pelamis units was installed off the northern coast of Portugal but was towed back to land when it encountered technical problems (partnership Enersis and Babcock & Brown). Pelamis submitted a proposal for a 7.5 MW farm of 10 units to be installed at the Wave Hub;
- a 40 kW Power Buoy prototype built by Ocean Power Technologies is operated by the US Navy in Hawaii (United States). This system is sufficiently mature to qualify for a 40 kW demonstration project (in partnership with Iberdrola and Total). Power Buoy is also a candidate for demonstration projects at EMEC in Scotland and at the Wave Hub (5 MW project);
- a 100 kW demonstration project of the Power Resonator system developed by Sync Wave Energy is planned for late 2009 on Vancouver Island (Canada).

The Oyster seabed systems from the Scottish firm Aquamarine and the Swedish company Seabased need to prove their efficiency through demonstration operations at EMEC.

Likewise the Australian system CETO, with support from EDF EN, has plans for 200 MW of capacity at five sites in Mauritius.

Technological bottlenecks

The technological bottlenecks of wave energy converters depend on the type of system and on its location. The principal obstacles facing the development of land-based systems is not necessarily technological but rather socio-economic: system profitability, environmental integration, acceptance by local residents.

The following points are critical requirements for wave energy systems:

- ability to survive extreme sea conditions for autonomous installations,
- maintenance held to a minimum,
- fatigue resistance (4 000 000 cycles/year),
- real-time remote control,
- on-board storage.

The technological bottlenecks that affect offshore systems are not specific to this technology, and are described in section 4.

> 8. Wind energy at sea

Offshore wind turbines exploit sea winds to generate electricity that is transported to land via underwater cables.

Up until today offshore wind projects have transposed a proven land-based technology to installations at sea. This more or less direct transposition had the advantage of enabling the rapid creation of an industrial wind energy production chain. But this approach quickly reached its limits, imposed in particular by the depths in which wind turbines could be installed: today 40 m seems to be the maximum. In addition, as the installation depth increases so do the quantities and therefore costs of steel and concrete materials for the foundations, along with the stresses on the structures.

Finding ways to bypass the constraints of sea depth is therefore an attractive option, particularly in France where water depths rapidly exceed 40 m even close to the coastline. While the North Sea offers vast plateaux in relatively shallow waters, the most interesting offshore wind energy zones in France are found along the coast of the Manche *département*, where conditions are much less favourable.

The future development of deepwater wind energy probably lies in new concepts that are not extrapolated from land-based wind energy technology. The challenge is to make use of the specific features of the sea environment rather than try to overcome them. Constructors of land-based wind turbines are prisoners of a single technology: innovations will come from marine builders who have new concepts.

The developers of floating wind energy projects offer a new look at this technology, opening the way to offshore wind installations in depths of over 50 m and farther away from the shore.

While there is a substantial technology transfer between land-based wind energy and wind installation in shallow waters, developed by the same players and using the same range of products, a technological breakthrough is needed to advance floating deepwater wind technology. The breakthrough will allow new actors to enter the market, coming from the offshore oil industry and naval construction in particular.

Potential exploitable resources

According to a survey conducted by the International Energy Agency in 2000 the technically exploitable potential of offshore wind energy in Europe is on the order of 313 TWh/year, for sites 20 km at most from the coast and in waters 20 m deep at most. The study envisions the use of floating wind turbines in the future that could be anchored to the ocean floor, allowing access to deeper waters. Floating turbines would open up potential areas for the development of wind farms off the shores of many countries, including France, Norway, Portugal, Italy, the United States. With the expansion of accessible areas the potential resources would be much greater.

Technologies under development

Floating wind turbines offer an promising technology for exploiting wind energy at deep sea locations (depths of over 50 m), a specific feature of French coastal waters.

Several solutions are proposed for floating wind turbines:

- floating column or tower with large draft, also called spar. The lower section of the cylinder is weighted to provide stability by gravitational forces. In one variant of this system the column can be moored to the ocean floor with a pre-tensioned axial cable to limit tilting due to horizontal stresses;
- semi-submerged floater with floats below the free surface, moored with slack lines;
- tension-leg platform (TLP) with one or more floats held underwater by tensioned (taut) anchor lines that are essentially vertical. The cables are pretensioned so that the moorings are never completely loosened by horizontal stresses on the turbine.

Floating wind turbine platforms should make it possible to reduce installation and maintenance costs. They can be assembled at a port and towed to their final location for mooring.

Conception and design of floating wind power installations is also an opportunity for French companies in naval and petroleum-industry engineering, outfitters, shipyards, maintenance and service industries to establish themselves in the sectors of offshore wind components and systems.

International benchmarks

Few floating wind energy projects exist today. The most advanced project is conducted by Blue H. A prototype unit consisting of a two-blade 80 kW turbine moored by tensioned cables was installed in the Adriatic Sea in 2008. A 2 MW demonstration wind turbine installation is planned for 2010.

Other projects are still in the concept stage.

The Hywind concept developed by StatoilHydro in Norway consists of a 200 m floating steel spar, half of which is underwater, anchored by three mooring lines. The 2.3 MW turbine is conventionally faced into the wind. Testing in basin conditions has been completed and the first prototype is to be built in Spring 2009.

For deepwater sites it is possible to take advantage of the floating structure to turn the turbine into the wind, rather than attempting to reproduce stable structures that maintain the turbine positioned into the wind. This allows for lighter structures. One example is the Norwegian Sway project: the turbine spontaneously swings to stand back to the wind, while the nacelle is held in a fixed position on the mast. Floating platforms can support turbines of up to 5 MW, in depths ranging from 80 to 300 m. Mooring systems are sensitive to variation in depth due to tides, however. A 5 MW prototype is expected to be deployed in 2010, for commercial operation in 2012.

The Windsea concept developed by Statkraft of Norway involves three turbines on a semi-submersible floating platform, with a total capacity of 10 MW. Two turbines face into the wind, while the third is downwind and triggers the orientation of the floater. The anchoring and electrical connection systems are equipped with a rotating link similar to anchoring turrets used in offshore oil wells. The project is being tested in a wave basin, and a prototype could be erected in 2011.

Other concepts are based on the development of small capacity (300 kW) floating vertical-axis turbines, such as the project developed by the U.S. company Floating Windfarms.

Technological bottlenecks

Design of floating wind turbines must take the following factors into account:

- structural stability to resist toppling under the wind,
- for horizontal-axis turbines the rotor must be placed perpendicular to wind direction,
- water depths over 50 m, and often over 100 m,
- exposure to unbuffered sea swell,
- exposure to storms that provoke major stresses on mooring lines and can project large quantities of water above the surface. (In this respect large horizontal-axis turbines are at an advantage compared to vertical-axis turbines with blades turning at low heights above the water.),
- variable water depth depending on tides,
- floating platforms subject to more or less pronounced movements, depending on the technology,
- ocean floor anchoring that can resist strong horizontal and vertical action,
- long distance to land, and hence long power cable for grid connection,
- high total capacity for the wind farm.

The turbine unit deployed on a floating wind energy platform must be designed with specific operating conditions in mind:

- the top mass of the turbine has a determining effect on the size of the floater required to ensure stability. The design must lower the mass as much as possible to lighten the nacelle. The smaller the floater the less it is subject to hydrodynamic forces, lessening stress on the anchoring lines;
- for horizontal-axis turbines the rotor can be equipped with three blades (as in most land-based turbines) or two blades. Two-bladed turbines turn at a faster speed than three-bladed ones and are more noisy, but this is not a drawback at sea. Higher rotation speeds also allow for a lighter gearbox and/or generator;
- a horizontal-axis rotor can be held facing into the wind (as is the case for most land-based wind turbines) or positioned downwind of the mast. In this second case the mast can be slightly tilted without problems, so that the floater can be lighter. To eliminate the effects of the mast wake or shadow, the mast can be equipped with airfoils, as is the case in the Sway project mentioned above;
- the oscillation movement of the floater has dynamic effects on the nacelle and the blades;
- apparent wind speed is subject to additional fluctuation due to turbulence introduced by pitching. Studies to anticipate blade fatigue must take this effect into account. Inversely, when the turbine is in operation pitching of the floater is limited by the rotor. This ceases when the turbine is stopped during storms.

Concerning grid connection, the specific feature of floating turbines is the need to connect wind farms of high installed capacity that are far from the coast. High transmission voltages are necessary, as well as DC transmission if this proves to be efficient. Power transformation platforms can be used to convert current between the deepwater wind farm and the coast, as is case for conventional bottom-mounted wind farms. It would be difficult to install these platforms in deep water on the high seas, however. Another solution is to convert the current at each floating turbine. This raises the problem of dynamic high-voltage cables and the feasibility of high-voltage electrical connections in marine environments.

> 9. Ocean thermal energy

Potential exploitable resources

Ocean thermal energy conversion (OTEC) exploits the temperature difference of at least 20°C between cold deep waters and warm surface waters to produce electricity. The same process can also yield fresh water, cooling for air conditioning, and derivative commodities for aquaculture, depending on the type of cycle used (open or closed). The theoretical global resource based on a temperature gradient of at least 20°C would allow production of approximately 10 000 TWh/year in subtropical zones[6]. Without massive energy storage this theoretical resource can be exploited only very partially and intermittently, due to the absence of electricity demand near the potential resource, e.g. in the Pacific subtropics. Storage in the form of hydrogen can be envisioned in the long term.

France was a precursor in OTEC technology, with work by G. Claude in the 1930s and by IFREMER in the 1980s. OTEC plants are suitable for baseload electricity generation (predictable and continuous) in subtropical zones.

The Exclusive Economic Zone of French overseas departments and local authorities provides a particularly interesting area for testing OTEC and contributing to energy independence in these outlying and isolated territories. The major advantage of OTEC is that the energy produced can be used night and day and year round, and it should be considered as an alternative to fossil fuels.

Another thermal use of the oceans, in temperate zones, is to use surface water as a heat source for heating/cooling via a heat pump (Sea Water Air Conditioning, or SWAC).

The availability of cold deep water could also provide an opportunity to experiment with other value chains based on the properties of this nutrient-rich water, aquaculture for example.

In light of the stakes–to provide baseload electricity for overseas communities–even if demonstration of technological maturity is possible on a small scale, only technologies suitable for floating generating plants of several MW are eligible.

Work already carried out in this area has shown that implementation of OTEC involves technological risks, in particular related to deepwater pumping pipes.

A floating platform for an energy converter larger than 1 MW is costly, and calls for using technologies borrowed from the oil industry, with little research involved.

Technologies

In this context the power to be supplied by OTEC is such that regardless of the technology used a very large ocean surface area would be required for energy conversion devices. Land availability and of course the tourism industry in overseas departments and communities make offshore solutions preferable.

Different thermodynamic cycles can be used to extract energy from the small temperature difference between surface waters and deep ocean waters.

There are two types of cycle:

- open cycle, in which the working fluid is sea water,
- closed cycle in which the working fluid is a refrigerant.

6 - An IEA-OES study estimated world potential at 10 000 TWh/year (IEA-OES, 2006: Review and analysis of ocean energy systems development and supporting policies).

Technological bottlenecks

It is quite probably possible to demonstration OTEC using existing technologies. To achieve this goal technological and environmental risks must be examined to address the following issues:

- storm resistance,
- cold water pipe,
- performance over time, in particular susceptibility to biofouling,
- environmental impacts, in particular releases in deep waters.

Other pathways should also be explored for more efficient use of this small temperature gradient that could make this energy resource economically viable. Some areas of focus:

- energy carrier,
- optimisation of existing thermodynamic cycles,
- research into new cycles,
- exchangers.

The need for demonstration of this technology applies above all to large offshore facilities because this is the type of installation this is most likely to correspond to the challenge of producing baseload power locally for overseas communities.

Only technologies suitable for 1 MW power plants minimum can be considered. Economic models indicate that plants of less than 10 MW installed capacity are unlikely to be profitable in the long term.

International benchmarks

Ocean thermal energy conversion relies on concepts that have been known since 1881, when Arsène d'Arsonval proposed a thermodynamic conversion process using the Rankine cycle (by analogy with a steam turbine).

Work to develop this value chain started in earnest in the 1920s with work by Georges Claude and Paul Boucherot. In 1928 G. Claude experimented with an open-cycle process using the cooling waters of a blast furnace in Ougrée, Belgium as a warm source and water from the Meuse river as a cold source. He was able to generate 60 kW with a temperature difference of 20°C. G. Claude demonstrated his system at sea in the bay of Matanzas, in Cuba. The temperature difference was only 14°C. The project produced electricity for 11 days before a storm destroyed the pipe.

The first American publications devoted to OTEC in 1965 refer to the work done in France and to the unfortunate experiments done by G. Claude. A preliminary project for a 100 MW floating closed-cycle plant was drawn up by J. H. Anderson, prefiguring projects developed later by major industrial companies in the United States, including Lockheed, TRW, General Electric and Westinghouse. Research work in the United States became more formally structured and intensified from 1973 on, under the twin pressures of the oil crisis and opposition to nuclear power. The Energy Research and Development Administration (ERDA) and then the Department of Energy (DOE) spearheaded industrial research on OTEC, focusing mainly on closed-cycle systems. The growing interest in OTEC was marked by the construction of the Natural Energy Laboratory of Hawaii (NELH). Work on land-based closed-cycle evaporators and condensers began in 1975. A mini-OTEC floating closed-cycle plant of 50 kW capacity, using ammonia as a working fluid, was mounted on a barge anchored in 900 m of water. The system was operated for four months, and dismantled in 1979.

In 1979 DOE funded the creation of a floating laboratory called OTEC-1 to develop seawater–ammonia exchangers. The laboratory, set up on a former U.S. Navy supply ship, was supplied with water pumped from 700 m below and operated for several months at a thermal capacity of 35 MW. In addition to the experience acquired with exchangers, the mini-OTEC and OTEC-1 experiments enabled American industrial companies to validate their installation procedures and the seaworthiness of equipment for future OTEC plants.

Like the Americans the Japanese were concerned about their energy dependence and the resulting vulnerability of their economy, and in 1974 undertook an ambitious renewable energy programme, the Sunshine Project, that included OTEC with the goal of demonstrating the economic feasibility of 100 MW plants by 1990. To fulfil this goal they built:

- 1979: a mini-OTEC plant using a closed cycle and freon working fluid, moored off Shimane in the Japan Sea;
- 1980: the experimental closed-cycle freon plant built on shore at Nauru that generated 31 kWh during several months of testing before it ended in 1982;
- 1982: a small 50 kW closed-cycled OTEC plant using ammonia on the island of Tokunoshima south of Kyushu island.

In 1986 falling oil prices on the world market accelerated the withdrawal of public funding for OTEC development. This withdrawal was total in France, severe in the United States and tangible in Japan. The result is a new global playing field in terms of exploitation of ocean thermal resources, now incontrovertibly dominated by the United States and Japan.

The need to be competitive and reduce the cost of the energy produced obliged American and Japanese researchers to focus on enhancing the value of deep water, which is cold and rich in nutrients. The Deep Ocean Water Application developed at NELH covered the following aspects:

- energy savings: how to use cold effluent streams for air conditioning,
- fresh water production based on condensation of water vapour from humid tropical air on cold effluent circulation pipes,
- growing algae using cold deep water streams to take advantage of their minerals and low presence of pathogenic organisms and substances, and to adjust cultivation tanks and basins to the needs of the crops,
- using deep waters for therapeutic and culinary purposes, to produce cooking salt and sake.

In parallel, and sometimes in bilateral projects, Japan and the United States continued their work to increase the efficiency of power production. NELH and the Pacific International Center for High Technology Research (PICHTR) worked together from 1993 to 1998 to construct and then test a mini onshore 250 kW open-cycle plant.

Japan and India deployed a 1 MW floating power plant on the Sagar Shakti barge in 2001. The plant was to be equipped with a pipeline measuring 88 cm in diameter and 1 km long, moored to the southern edge of the Indian continent, that ruptured when it was put into the water. This project was not pursued for electricity generation.

For the last 20 years the United States and Japan have managed to maintain some momentum in their search for technical and economic solutions that make OTEC more and more attractive. They have optimised component performance (exchangers and turbines), consolidated the confidence level for marine equipment, notably construction and installation of deep water pumping pipes, and developed the concept of multi-product OTEC plants of up to several tens of MW in capacity. This plant concept that seeks to exploit cold deep waters for air conditioning, freshwater production and commodities for aquaculture, among others, is particularly suitable for remote coastal communities that are close to the resource.

They have also studied the possibility of extrapolating the OTEC value chain to floating factories of several hundred MW for at-sea production of synthetic liquid fuels (hydrogen, ammonia, methanol) that could be transported by tanker to meet the primary energy needs of industrialised countries that are far from the places where OTEC resources are available.

Lastly, the data acquired through the operation of experimental sites gives them a sense of the impacts, positive and negative, caused by the release of mineral-rich cold deep water to the surrounding environment, and enables them to sketch out the boundaries determining sustainable resource use.

For these reasons the main actors in the value chain today are American or Japanese, including:

- Lockheed Martin, system supplier and leading military shipbuilder (USA),
- Xenesys (Japan),
- Makaï Ocean Engineering equipment manufacturer (USA).

Recent experimentation has validated the use of sea water to produce both cooling and heating. Cold-water air-conditioning systems are distinct from cooling/heating systems based on heat pumps. In tropical areas direct cooling systems using pumped sea water are used to cool five commercial buildings in Curaçao (installed by the Dutch firm Seacon International) and 80 bungalows in Tahiti (a 1 500 kW system built by Odewa). The U.S. corporation Market Street Energy has built a 60 MW temperate-zone cooling network in Stockholm. Air-conditioning systems coupled with heat pumps are used to cool and heat homes and offices in La Seyne-sur-Mer (net capacity 493 kW).

> 10. Marine biomass

Potential exploitable resources

Algae are a set of photosynthetic organisms with diverse characteristics. They cannot be defined and grouped in a single coherent family. Even restricting the focus to single-cell microalgae, classification is not easy. There are hundreds of thousands of species spread all around the world, in salt water, fresh water and brackish water habitats. Algae account for 90% of primary aquatic production and 50% of primary production globally. They have colonised all environments, from the polar ice caps to deserts and hot-water springs. They have adapted to extreme conditions, and live in salt marshes, acidic environments, and even in places with very little light. By their presence at the surface of the oceans that cover 70% of the globe, algae transform CO_2 into organic matter and thus play a major role in the climate of the planet.

Estimates of the number of existing species of algae range from 200 000 to one million, and this little exploited diversity holds vast possibilities for research and industry.

This biological diversity, sign of exceptional adaptability, presages proportional riches of singular molecules and of course lipids. Compared to oil-rich land species, microalgae possess many characteristics that favour production of fatty acids.

The strong points of microalgae include:

- per hectare growth and potential production higher than for oil-rich land species,
- no conflict with food crops,
- much greater metabolic flexibility, making it easier to adapt bioproduct to produce certain fatty acids,
- control of nitrogen and phosphorus cycles through recycling of nutrients,
- possible coupling with an industrial CO_2 source,
- continual crop yields,
- no addition of fertiliser or plant protection products,
- no conflict in water management if grown in sea water,
- many valuable byproducts,
- technology suitable for operations in developing countries.

Technologies

The basic principle is to gather or grow either macro or microalgae in order to extract respectively sugars and oils.

It is important to make a distinction between cultivation in controlled photobioreactors with natural or artificial light that offer high yields with high investment and operating costs, and natural production in natural lagoons or extensive tubing that have lower costs and lower yields.

An important advantage of algae-based fuels, that have already been called third-generation fuels, is that they to do not compete with food crops or for fresh water resources. With rapid reproduction and better photosynthetic conversion microalgae achieve much higher yields in terms of vegetal matter than terrestrial crops. Oilseed rape and sunflower yields are 1 g/m2/day. Innovalg, based in Vendée (France) reports 13 g/m2/day for an open-air algae farm. IFREMER registers 30 g/m2/day in a controlled photobioreactor.

International benchmarks

Sixty companies in the world today claim to be working on microalgae and biofuels. The following projects are worth noting:

- Solix Biofuels (United States) is planning a 4 ha pilot installation for cultivation in photobioreactors,
- Aquaflow Bionomic (New Zealand) is planning open-air farms and will sued CO_2 emissions from power plants,
- HR Biopetroleum (Hawaii) is pursuing the same goal of CO_2 capture,
- Petrosun (Texas) is already cultivating 445 ha, plans to grow crops on 1 100 ha of pools and ponds, and has projects in Mexico, Brazil and Australia,
- Algatech (Israel) is already growing microalgae for pharmaceuticals and is working with the U.S. company GreenFuel to develop motor fuels,
- Solazyme (United States) is developing a method for cultivating modified microalgae based on sugar and fermentation and not on photosynthesis,
- Sapphire Energy, with support from Bill Gates, has obtained approval for an algae-based fuel with an octane index of 91, and plans to produce 10 000 barrels a day in three to five years,
- Algenol Biofuels (United States) has plans to grow cyanobacteria for bioethanol.

Technological bottlenecks

The main factors in lipids productions are stresses: low temperature, intense light, nitrogen limitation, severe phosphate deficiency, alkalinity and silica limitation for diatoms. These influences do not all have the same weight, and factorial analyses must be conducted to evaluate their interaction.

Producing biofuels from microalgae makes sense only if it makes the most of solar energy and uses a minimum of labour. No independent assessment has been made of the surface areas required for cultivation of these crops. How much land area is available in France and in Europe? How are the proximity of wastewater treatment plants, CO_2-emitting power plants, available seawater lagoons and cultivation basins to be coordinated? If crops are successful, what will be the impact of thousand of hectares of algae cultivation on the geography of national wetlands, and how can it be measured? Microalgae are very sensitive to strong light. Experiments in New Mexico, for instance, also show the impact of cold nights and of diurnal evaporation in desert climes. In winter the yields of outdoor crops are very low, falling to 2g/m2/day. These factors tend to dampen the declarations of countries with sunny climates who are seeking energy independence. The microalgae chosen for cultivation should have high and stable lipid content.

One solution could be to plan successive crops of different species that are optimally adapted for cultivation under seasonally different conditions. This stability applies to photosynthetic activity. Once again, while this option is entirely feasible, research remains to be done. Most studies neglect nutrient supplements, which need to be quantified, as well as the addition and fate of silica in the metabolism of diatoms. This point will have a decisive impact on production costs. Harvesting of microalgae is a crucial aspect that remains to be studied, and depends on technical advances in ultrafiltration and other process engineering solutions. Harvesting techniques will strongly affect costs.

The alternative to centrifugation is to choose an algae that flocculates readily or is easily separated by sedimentation. This type of algae calls for methods to maintain suspension, and thus consumes energy. The choice between freshwater and seawater algae can be made only on the basis of future studies.
Each type of algae has its advantages and drawbacks. If crops are grown in fresh water, conflicts over water use may arise. On the other hand, coupling with CO_2 sources will be less systematically available at coastal locations, or will at the very least have to be planned. Risk of contamination is high in open-air cultivation, whether by invasion of better adapted local microalgal species or zooplankton predators. Documented economic studies along the lines of those devoted to land-based biofuels remain to be produced and published. Plausible but very optimistic figures given in an American study have been elevated to the rank of certainty by citation in several popular science works, but they remain to be verified, if not established.

Thanks to the large amount of knowledge already acquired on this subject, it is possible to discern the obvious role that microalgae will play in the domain of renewable energy and CO_2 storage. Even if enthusiastic estimates of 100 to 150 tonnes of oil per hectare and per year should be divided by a factor of 5 or 10, microalgae present real advantages as listed above. It remains to formulate and list the points that need to be further studied. Among these a priority will be a real-life scale study with an analysis carried out by economists. IFREMER has definite strengths in this area, i.e. historic know-how and skills in cultivation of microalgae, exceptional access to biological resources in France and in Europe, and the infrastructure to envision literally all possible crop volumes. Using microalgae to produce oils is a logical complementary activity in the biofuels value chain, assuming that after professional analysis of intellectual property rights and current patents this pathway remains open.

> 11. Salinity gradient energy or osmotic energy

Potential exploitable resources

When a river flows into the sea the mixing of waters with different salt concentrations results in a loss of entropy. Useful energy can be recovered by directing the waters through semi-permeable membranes. Two energy recovery methods are being tested: one based on osmosis, in Norway, and the other using reverse electrodialysis, in the Netherlands.

A study by the Statkraft utility indicates that the global potential for salinity gradient power (SGP) could attain 1 600 TWh, across more than 180 sites (170 TWh in Europe)[7]. In Norway alone it is estimated that exploitation of this potential could cover 10% of annual energy needs.

Technologies

Three technologies exist for the exploitation of osmotic energy.

- Pressure Retarded Osmosis (PRO): fresh water and salt water are separated by a semi-permeable membrane. The fresh water migrates through the membrane, generating osmotic pressure. This pressure is used to vaporise a fluid that drives a turbine. The final products are a mixture of fresh and salt water, and electricity. This technology requires continually fed water reservoirs to stabilise power generation. It may call for filtration or pretreatment of fresh water. In the membrane module 80% to 90% of fresh water crosses the membrane into the pressurised seawater compartment. The resulting brackish water is divided into two streams: one-third drives the turbine, and two-thirds the pressure exchanger to maintain pressure in the seawater side. At present power production is on the order of 2.8 MW for a water flow of 1 m^{-3} s^{-1}.
- Reverse electrodialysis (RED): fresh water and salt water are separated by a selective ionic membrane. Saline ions migrate across the membrane, generating an electric current. Although the principle has been validated, pre-commercial development has been halted by membrane costs. Power production is on the order of 1 MW for a water flow of 1 m^{-3} s^{-1}.
- Vapour pressure difference utilisation (VDPU): The pressure of vapour from fresh water is different from the pressure of seawater vapour. This difference can be used to drive a turbine.

International benchmarks

There are few demonstration projects of osmotic energy converters used to produce electricity. As of today a single demonstration project, a 2 to 4 kW plant using PRO technology built near Oslo in 2008, has been undertaken by the Norwegian company Statkraft. This project is intended to pave the way for construction of a large plant in 2015. The firm Wetsus plans another 10-40 kW pilot project for 2009-2010 in the Netherlands.

Technological bottlenecks

This technology is the least mature of marine renewable energy technologies. It is restricted by membrane costs and capacities (roughly 3W/m2 today). Forward-looking studies on marine energy predict costs of different technologies in 2030. In the view of several authors, the cost of membranes will not have changed much from the 1977 level, i.e. $125 000/MW installed capacity. Other studies from the period 1975-1985 estimate the cost at between $0.02 and $1.30/kWh for PRO and RED technologies. Another preliminary study conducted in 1995 estimated the cost at between $0.035 and $0.07/kWh for PRO technology. The Norwegian developer Statkraft is counting on a provisional cost of between €40 and €50/MWh by 2015.

Technological breakthroughs are needed to lower these costs: salt-pump nano-biotechnology or electro-osmosis.

7 - Skråmestø, O. S.; S. Skilhagen, 2008 : Status of technologies for harnessing salinity power and the current osmotic power, Annual report 2008, IEA Ocean Energy Systems.

> 12. Perspectives for deployment of marine energies in 2020 and in 2030

IFREMER launched in March 2007 a prospective study of marine renewable energy in 2030, in liaison with some 20 partners in France representing the main actors in the sector: government ministries, research institutes, specialised agencies and the European Commission. The objective of this study is to help identify the issues at stake and the conditions for the emergence of the major technologies, considering estimated costs, technological and infrastructure constraints on land as well as at sea, and potential environmental impacts. This work relies on evaluation of the possible outcomes of some 30 key variables, that are contingent upon political and socio-economic contexts at global, continental, national and regional scales, on constraints in zones of production, and on the advancement of knowledge and technological progress. This study highlights four intentionally contrasting scenarios.

Scenario 1: Energy crisis and emergency

This scenario posits that the market is in a state of **energy crisis** and **economic competition**. The prime objective is **mastering the most competitive and suitable technologies** via strong strategic partnerships. Without strong political support investments are made by groups of private operators who favour development based on progressively larger "demonstrators". Recurrent conflict over access to space leads to the creation of dedicated parks and farms, eventually with multiple uses. Research is turned towards technological improvement, the key to competitiveness, and towards better understanding of impacts.

This context is favourable to proven technologies: wind energy, tidal energy and ocean thermal energy. Due its strategic advantages biomass is rapidly and extensively developed. Hybrid systems are explored, notably to optimise investments. Wave and current energy are given little or no attention, for lack of short-term profitability.

Scenario 2: Virtuous cooperation by necessity

This scenario is determined by a **political commitment to sustainability at the international level** with steady extension of the Kyoto agreement. The major consequence of this is **support for research and the least mature technologies** in order to encourage private investment and diversify technological choices. This work tends to foster risk taking in relation to new technologies and their hybrid combinations, leading to mastery of energy storage and opening the way to large-scale offshore and deepwater systems. Research is devoted to new concepts aiming to minimise environmental impacts.

The worldwide movement brings forth many technologies: deepwater marine current machines, artificial lagoons, deepwater (>50 m) wave energy systems, floating wind turbines, ocean thermal energy in association with aquaculture, large-scale biomass (intensive land-based crops, GMOs and multi-products), osmotic energy (development of economical membranes with a few micro power plants). This flourishing of technologies is favourable to hybrid uses, particularly in overseas departments and communities.

Scenario 3: Slow or no change, each for himself

This scenario is characterised by **little international cooperation and defence of national interests and energy security.** The main issue is controlling energy sources nationally, as tension and protectionism are on the rise. After affecting the South, worsening climate change drives a growing need for fresh water in the North. Public funds are devoted to energy security, but at low cost, with the consequence that electricity grids are not maintained to accommodate decentralised production, and feed-in tariffs expire after 2020. Dedicated energy farms emerge and technologies develop independently, leading to specialised research on environmental impacts by type of technology.

This situation leads to slow development for almost all technologies, because public and private investors prefer security to taking technological risks. Independent development of technologies hinders the quest for synergy in funding as well as in shared knowledge of impacts.

Scenario 4: Autonomous local development

Local development with acceptance of risk against a backdrop of rising tension and protectionism, as well as the need for energy security, are the prominent features of this scenario. The need for fresh water, in the North as well as in the South countries, justifies both the technological search and decentralised initiatives. Intensively cultivated biofuels (photoreactors) become profitable (tax breaks phased out by 2015) and public support (via regional governments) are aimed at mastering technology as well as competitiveness.

These dynamics lead to reinforcement of power grids to accommodate decentralised generation and to technological development differentiated by region and according to their specific features. Research work backs technologies in relation to local opportunities and supports local demonstrators. This trend and the accompanying risks imply strong involvement of political decision-makers to facilitate public acceptance of experimentation.

The technological consequences are economies of scale attainable only the worldwide level, and the emergence of multiple niche markets. Wind energy, ocean thermal energy and biomass reach industrial production levels, while other technologies develop locally on a small scale. Research remains fragmented, highly focused on local constraints with coastal universities in the leading role, aided by regional governments.

Qualitative vision for 2030

The variables and assumptions used to construct the four scenarios are given in Table 1.

	Scenario 1 **Energy crisis and emergency**
Background	Energy crisis and economic competition
Energy stakes	Technological partnerships and market competition
Political support	May the best (man) win! Investment by groups of private operators Marketing of demonstrators
Development context	Conflicting development, with dedicated parks at multi-use sites
Research	Technological development and impact studies
Impacts on technology	Proven technologies
Marine current energy	Medium to little development Restricted to surface or shallow-water turbines
Tidal energy	Strong development of barriers and aquaculture
Wave energy	Medium to low development only close to shore (depth < 50 m) or at the edge of wind or current energy farms
Biomass	Extensive development on prepared land Development abroad
Wind energy	Strong development via adaptation of land-based turbines (bottom- mounted)
Ocean thermal energy conversion	Medium development Mainland France: Heat pumps, occasionally air conditioning Overseas: Especially at remote sites, cooling, electricity, water
Osmotic energy	No significant development
Hybrid technologies	Development of multi-use sites
Order of development of value chains	Wind (bottom-mounted) Tidal energy OTEC cooling in the tropics OTEC air conditioning in mainland France Biomass OTEC electricity in the tropics Marine current energy Wave energy Osmotic energy

Table 1: Hypothesis for construction of four prospective studies for 2030

Scenario 2 Virtuous cooperation by necessity	Scenario 3 Slow or no change, each for himself	Scenario 4 Autonomous local development
Worldwide cooperation and Kyoto II	Little worldwide cooperation	
Public private investment	Rising tension, protectionism, security concerns	Rising tension, protectionism, security concerns
Support for research and the least mature technologies	Low-cost security No grid decentralisation Feed-in tariffs phased out after 2020	Support for research and decentralised systems
Acceptance via consultation		Social acceptance of experiments
New concepts and hybrids: environmental impacts	To each his own technology; impact studies	
Development of all technologies	Minimum development, dedicated parks by technology	Grid decentralisation and technological development according to project location
Deepwater turbines, including ocean currents	Submerged current turbines	Niche market
Development + other uses	Naturally favourable sites Electricity generation only	No development
Exploitation close to shore (depth < 50 m); remote sites	Exploitation close to shore (depth < 40 m)	Exploitation close to shore (depth < 40 m) Remote sites
Intensive terrestrial production GMOs and multi-products	Production limited to high-tech products	Intensive terrestrial production Selection of strains
Floating wind turbines	Adaptation of land-based turbines	Floating and conventional turbines
Air conditioning in the North Air conditioning, water–electricity for tropical sites Biological recovery of nutrient salts and minerals from deep waters	Air conditioning in the North Air conditioning, water–electricity for tropical sites	Air conditioning in the North Air conditioning, water–electricity for tropical sites
Pilot project for a micro power plant	No development	Pilot project for a micro power plant
Pro-active development	Independent development	Independent development
Wind energy Biomass Wave energy OTEC cooling in the tropics Marine current energy Tidal energy OTEC air conditioning in mainland France OTEC electricity in the tropics Osmotic energy	Wind energy Marine current energy Tidal energy OTEC cooling in the tropics OTEC air conditioning in mainland France Wave energy OTEC electricity in the tropics Biomass Osmotic energy	Biomass Wind energy OTEC cooling in the tropics OTEC air conditioning in mainland France OTEC electricity in the tropics Tidal energy Wave energy Marine current energy Osmotic energy

Quantitative vision for 2030

To compare energy production scenarios we have built scenarios with figures for France and its overseas departments and communities. The estimated contribution of renewable marine energy to energy production is to be taken only in this context. The order of technologies drawn from the quantitative comparison (by order of magnitude) of the various scenarios would be different in other national contexts. Each country possesses its own marine energy resources to be exploited.

Island energy needs, and particularly French overseas departments and communities, influence the technological choices found in these scenarios, and all the more so that renewable energy technologies are structurally more profitable on many of these distant islands than on the continent. This diverse geographical situation is beneficial for France.

It offers outlets for technologies such as OTEC that are best suited to South countries.

Regardless of the technology envisioned, the potential is still often shrouded in major uncertainty, for figures quoted in different studies vary by a factor of as much as 10, in particular for exploitable potential resources.

Table 2 displays the contribution of each value chain to energy production in France and in overseas territories, under each of the four scenarios.

This study shows that development of value chains varies widely from one scenario to another. For power production, installed capacity may vary by a factor of 5 for wind or marine current energy, up to a factor of 20 for wave energy.

Table 2: Quantitative evaluation of renewable marine energy production according to four prospective scenarios for 2030

	Scenario 1 Energy crisis and emergency	Scenario 2 Virtuous cooperation by necessity	Scenario 3 Slow or no change, each for himself	Scenario 4 Autonomous local development
Marine current energy (TWh/year)	0.3	3.0	0.6	0.2
Tidal energy (TWh/year)	1.0	1.5	0.6	0.6
Wave energy (TWh/year)	0.3	6.0	0.3	0.5
Wind energy	12.0	30.0	6.0	12.0
OTEC overseas territories (TWh/year)	0.4	0.7	0.2	0.7
Osmotic energy (TWh/year)	0.0	0.0	0.0	0.0
OTEC air conditioning mainland France (TWh/year)	3.15	0.12	6.30	0.4
OTEC air conditioning mainland France (TWh/year)	3.15	15.84	1.60	15.80
OTEC fresh water overseas territories (Mm3/year)	1.7	3.3	0.8	1.25
Biomass (Mtoe)	0.05	2.50	0.00	1.25
TOTAL	Electricity: 14.0 TWh/year Cooling: 6.30 TWh/year Fresh water 1.7 Mm3/year Motor fuels: 0.05 Mtoe	Electricity: 41.2 TWh/year Cooling: 15.96 TWh/year Fresh water 3.3 Mm^3/year Motor fuels: 2.5 Mtoe	Electricity: 7.7 TWh/year Cooling: 7.9 TWh/year Fresh water 0.8 Mm3/year Motor fuels: 0 Mtoe	Electricity: 14.0 TWh/year Cooling: 15.84 TWh/year Fresh water 3.3 Mm3/year Motor fuels: 1.25 Mtoe

Quantitative vision for value chains in 2020

A normative scenario outlining the breakdown of different marine energies within an overall objective of a 3% share (excluding offshore wind energy) of renewable energy in total final energy consumption in France in 2020 is suggested in this prospective view of marine energy.

This scenario investigates the part that renewable marine energy could play to reach the 20% renewable energy goal for 2020 under good environmental and feasibility conditions. This assumes that the share of renewable energy in the 2020 energy mix will rise by 20 Mtoe, following the two strategic directions of decentralisation and increasing autonomy "wherever possible" (Jean-Louis Borloo, Environment Minister, 26 December 2007).

This scenario attempts to realistically select technologies that are likely candidates for development and estimate capacities and production from projected figures. Estimated development of value chains is given in Table 3. This scenario is meant to assess the organisational work, research and industrial progress to be achieved in order for each technology to make its contribution if appropriate. Marine energy technologies will have their share if networks of strategic partnerships and pre-industrial or even industrial experiments (offshore wind, marine biomass, or ocean thermal energy) are in place by 2020.

The estimated contribution of deepwater floating wind turbines to this scenario has been added after consultation with professionals.

Under this normative scenario, renewable marine energy would contribute 17.2 TWh or 3.2% of total electricity consumption in France in 2020 (an estimated 530 TWh, see table 4), which is far from negligible.

Considering technological progress, including breakthroughs such as hydrogen energy storage, along with improved energy yields and energy savings, particularly in cities, one can reasonably expect faster growth in the marine energy share between 2020 and 2030, which could by then represent 4% to 5% of French electricity consumption, or more, depending on global circumstances.

Table 3: Development objectives under the normative scenario for

Value chain	Installed capacity (MW)	Electrical power (TWh)	Energy (Mtoe)	Share (%) under Grenelle objectives for 2020
Marine current energy	400	1.4	0.12	0.6
Tidal energy	500	1.25	0.11	0.5
Wave energy	200	0.8	0.07	0.3
Wind (bottom-mounted)	4 000	12	1.03	5.2
Wind (floating foundations)[8]	1 000	4	0.33	2
OTEC electricity overseas territories	200	1.4	0.12	0.6
Osmotic energy	0	0	0	0
OTEC cooling avoided in mainland France[9]	55	0.4	0.03	0.2
OTEC cooling avoided in overseas territories	40	0.3	0.02	0.1
Biomass	-	-	0.07	0.3

8 - Estimates from SAIPEM.

9 - Assuming that 1 kWh of cooling energy is equal to 0.22 kWh.

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The French Environment and Energy Management Agency (ADEME) is a public agency under the joint authority of the Ministry for Ecology, Energy, Sustainable Development and the Sea, and the Ministry of Higher Education and Research. The agency is active in the implementation of public policy in the areas of the environment, energy and sustainable development.

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Ref. : 6908 - ISBN : 978-2-35838-186-4 - August 2010 : AXEL Client.com - Photo : O. Diaz (offerte par Sabella)

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