SIXTH FRAMEWORK PROGRAMME

Project no: **502687**
NEEDS
New Energy Externalities Developments for Sustainability

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Sub-priority 6.1.3.2.5: Socio-economic tools and concepts for energy strategy.

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1 Contents

Abbreviations

a	year
CDM	Clean Development Mechanism
ct€	Euro-Cent
kW	Kilowatt (electrical)
kWh	Kilowatt-hour (electrical)
MW	Megawatts (electrical)
GW	Gigawatts (electrical)
GWh	Gigawatt-hours (electrical)
TWh	Terawatt-hour (electrical)
OWC	Oscillation water column
H_z	Wave period in sec

2 Summary

The objective of this report, as part of the NEEDS project, is to provide data on costs and the life cycle inventories for offshore wave and tidal energy technologies. The focus is the present and long term technological development of the wave and tidal energy technology.

The first part of the report deals with the State-of-the-Art of the technologies. The aim is to be able to define a reference technology to be used in the remaining part of the report. Caused by the infantry of the industry where only at the end of 2008 the first pre-commercial devices were deployed not much detailed information has been available.

The second part deals with the future technological developments. In this section the technological and non-technological barriers and drivers are discussed. On the basis of the barriers and drivers three scenarios are described, based on a conservative (*pessimistic development*), moderate (*optimistic-realistic development*) and optimistic (*very optimist development*) scenario for the future wave and tidal energy technology. The road maps describe in detail how the technologies of wave and tidal energy could develop and how costs could develop in respect to projections of installed capacity and experience curves.

In the optimistic scenario it is concluded that the development of wave and tidal energy after 2025 can be described as a “self-runner”, i.e. that the wave and tidal technologies can compete with traditional oil and gas technologies if taking the most basic externalities into consideration.

In the moderate scenario it is projected that wave and tidal energy devices have an investment cost of 1,200 €/kW and a production price of 0.04 €/kWh by 2050 and in the optimistic scenario it is projected that wave and tidal energy devices have an investment cost of 1,000 €/kW and a production price of 0.03 €/kWh by 2050.

The installed power is by 2050 in the moderate scenario projected to be 194GW and in the optimistic scenario to be 309GW.

The third part of the report deals with the life cycle inventories for the present and future wave and tidal energy technologies. One of the technologies Wave Dragon has been selected as reference technology and the data are described and analysed in the last section of the report.

<u>About the NEEDS project [19]</u>

The ultimate objective of the **NEEDS Integrated Project** is to evaluate the full costs and benefits (i.e. direct + external) of **energy policies** and of **future energy systems**, both at the level of individual countries and for the enlarged EU as a whole.

In this context NEEDS refines and develops the externalities methodology already set up in the **ExternE** project, through an ambitious attempt to develop, implement and test an original framework of analysis to assess the long term sustainability of energy technology options and policies.

NEEDS is supported by the Directorate General for Research of the European Commission in the context of the 6th Framework Programme.

3 Introduction

The purpose of this report is to provide a technology specification of the present state of the art of marine wave and tidal energy technologies. Besides a technical description the specification will contain a description of life cycle analysis (LCA) and investment cost parameters for the present technology level. These descriptions will form a basis for the extrapolation of LCA and cost data for the future marine wave and tidal energy technologies in accordance with the identified drivers and barriers for technological development.

The report includes forecast of production figures and market expectations for the defined 3 scenarios:

1. Conservative (pessimistic development)
2. Moderate (optimistic-realistic development)
3. Optimistic Very optimistic development)

In a report to the IPCC [3] the following figures are mentioned for the ocean energy market:

> Ocean Energy (OE) represents one of the largest renewable resources available on the planet. OE is an emerging industry that has a potential to satisfy world-wide demand for electricity, water and fuels, when coupled with secondary energy conversation principles.
> OE represents a number of energy conversion principles:
> - Wave energy is represented by surface and subsurface motion of the waves;
> - Hydrokinetic energy that harvests the energy of ocean currents and tides;
> - Ocean thermal energy conversion uses the temperature differential between cold water from the deep ocean and warm surface water;
> - Osmotic energy is the pressure differential between salt and fresh water.
>
> The theoretical global resource is estimated to be in the order of:
> - 8,000 - 80,000 TWh/year for wave energy;
> - 800 TWh/year for tidal current energy;
> - 2,000 TWh/year for osmotic energy;
> - 10,000 TWh/year for ocean thermal energy
>
> This has to be compared to the Worlds electricity consumption of 16,000 TWh/year (by 2005).

4 Wave power plants today

The following chapter are giving an update of the development within wave energy today. The report has been written during the last 2½ year where an enormous development has taken place. The chapter will therefore only mirror the basic development. A more comprehensive *State of the Art* can be found in the report to the EC Waveplam project [5] (www.waveplam.eu) and the EMEC homepage [6] (www.emec.org.uk).

4.1 Wave Energy Physics and Resources

Among different types of ocean waves, wind generated waves have the highest energy concentration. Wind waves are derived from the winds as they blow across the oceans. This energy transfer provides a natural storage of wind energy in the water near the free surface. Once created, wind waves can travel thousands of kilometres with little energy losses, unless they encounter head winds. Nearer the coastline the wave energy intensity decreases due to interaction with the seabed. Energy dissipation near shore can be compensated by natural phenomena as refraction or reflection, leading to energy concentration ("hot spots").

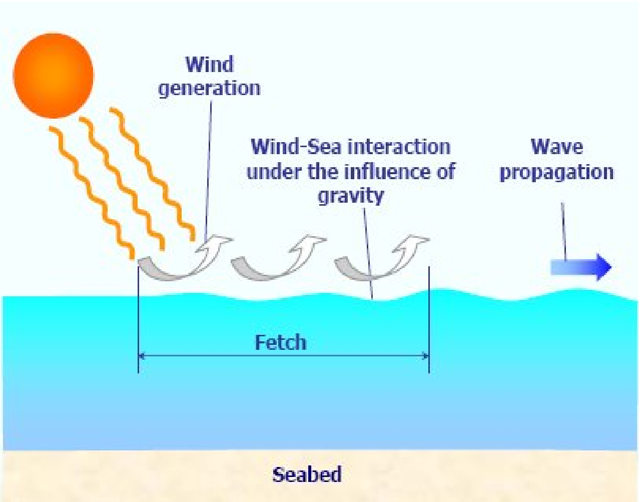

Figure 4-1: Generation of ocean waves, [2]

Ocean waves encompass two forms of energy: the kinetic energy of the water particles, which in general follow circular paths; and the potential energy of elevated water particles. On the average, the kinetic energy in a linear wave equals its potential energy. The energy flux in a wave is proportional to the square of the amplitude and to the period of the motion. The average power in long period, large amplitude waves commonly exceeds 40-50 kW per meter width of oncoming wave.

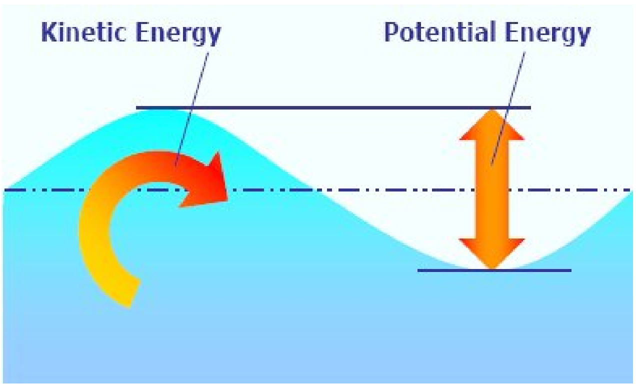

Figure 4-2: Energy in ocean waves, [2]

As most forms of renewables, wave energy is unevenly distributed over the globe. Increased wave activity is found between the latitudes of ~30° and ~60° on both hemispheres, induced by the prevailing western winds blowing in these regions, Figure 4-3. Particularly high resources are located along the Western European coast, off the coasts of Canada and the USA and the southern coasts of Australia and South America.

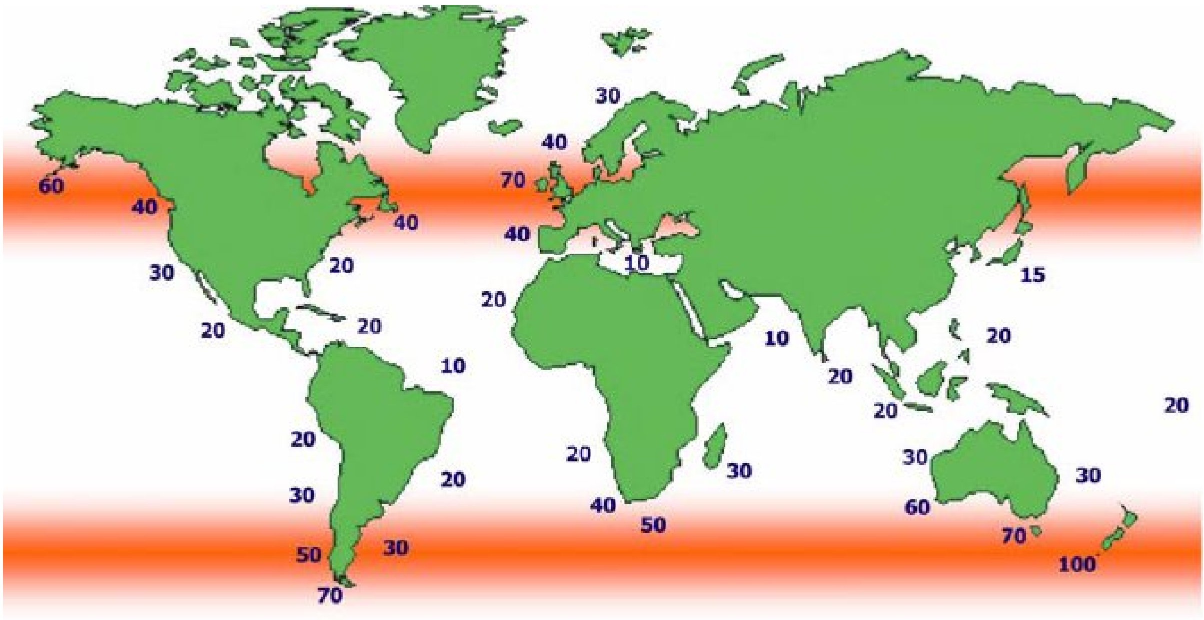

Figure 4-3: The highest wave activity (kW/m) is found between the latitudes of ~30^o and ~60^o on both hemispheres, [2]

Situated at the end of the long fetch of the Atlantic, the wave climate along the western coast of Europe is highly energetic. Higher wave power levels are found only in the southern parts of South America and in the Antipodes. Resource studies assign for the area of the north-eastern Atlantic (including the North Sea) available wave power resource of about 290GW and for the Mediterranean 30GW. The similar figure for the west coast of United States is 150GW.

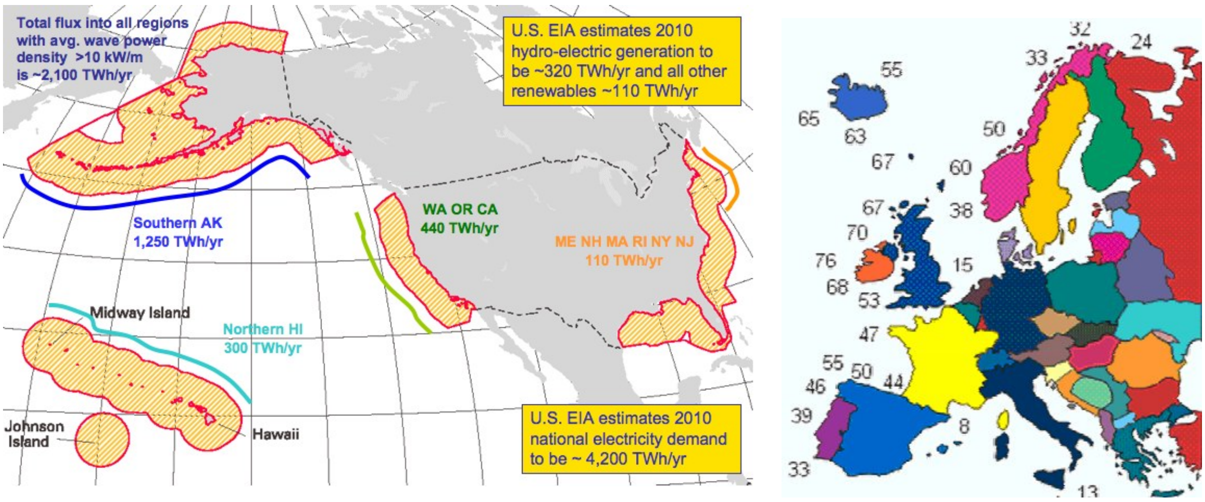

Figure 4-4: Right: The wave energy potential (kW/m) near shore at the west coast of Europe. Left: The wave energy potential expressed in potential electricity production (TWh) at the coasts of US [4] and [2].

4.2 Principles and Aspects of Wave Energy Conversion

In contrast to other renewable energy sources the number of concepts for wave energy conversion is very large. Although over 1000 wave energy conversion techniques are patented worldwide, the apparent large number of concepts for wave energy converters can be classified within a few basic types:

- **Oscillating Water Columns** are partially submerged, hollow structures open to the seabed below the water line. The heave motion of the sea surface alternatively pressurizes and depressurises the air inside the structure generating a reciprocating flow through a turbine installed beneath the roof of the device.
- **Overtopping devices**, floating or fixed to the shore, that collect the water of incident waves in an elevated reservoir to drive one or more low head turbines.
- **Heaving devices** (floating or submerged), which provide a heave motion that is converted by mechanical and/or hydraulic systems in linear or rotational motion for driving electrical generators.
- **Pitching devices** that consist of a number of floating bodies, hinged together across their beams. The relative motions between the floating bodies are used to pump high-pressure oil through hydraulic motors, which drive electrical generators.
- **Surging devices** that exploit the horizontal particle velocity in a wave to drive a deflector or to generate pumping effect of a flexible bag facing the wave front.

At the website for the European Marine Energy Centre [6] a list of developers are shown.

It is important to appreciate the difficulties facing wave power developments, the most important of which are:

- Irregularity in wave amplitude, phase and direction; it is difficult to obtain maximum efficiency over the entire range of excitation frequencies.
- The structural loading in the event of extreme weather conditions, such as hurricanes, may be as high as 100 times the average loading.
- The coupling of the irregular, slow motion (~0.1 Hz) of a wave to electrical generators requires typically ~500 times greater frequency.

Obviously the design of a wave power converter has to be highly sophisticated to be reliable and safe on the one hand, and economically feasible on the other. The abundant resource and the high-energy fluxes in the waves prescribe economically viable energy production. One of the important advantages of wave energy technologies is their environmental compatibility, as wave energy conversion is generally free of polluting emissions. Also, the low visual and acoustic impact, particular of offshore or submerged devices, is a major advantage over e.g. wind energy or photovoltaic.

It is one of the advantages of wave energy compared to wind energy that wave energy can be forecasted several days ahead. Holes in the energy content do not exist as is the case for offshore wind.

The negligible demand of land use is an important aspect, followed by the current trends of offshore wind energy exploitation. As for most renewables, the in-situ exploitation of wave energy implies diversification of employment and security of energy supply in remote regions. Furthermore, the large-scale implementation of wave power technologies will stimulate declining industries, e.g. shipyards, and promote job creation in small and medium-sized enterprises.

4.3 Wave Energy Development Status

Wave energy conversion is being investigated in a number of countries, particularly in the member States of the European Union, Canada, China, India, Japan, Russia, the USA and others. Although the first patent certificate on wave energy conversion was issued as early as 1799, the intensive research and development study of wave energy conversion began after the dramatic increase in oil prices in 1973.

In the last five years there has been an increasing interest in wave energy, especially in Europe. Recently wave energy companies have been highly involved in the development of new wave energy schemes such as the Pelamis, the Archimedes Wave Swing or the Wave Dragon.

The predicted electricity generating costs from wave energy converters have shown a significant improvement in the last twenty years, which has reached an average price at 20 c€/kWh. A price of less than 10 c€/kWh is expected as soon as mas production takes place. Compared, e.g., to the average electricity price in the European Union, which is approx. 4 to 6 c€/kWh, the electricity price produced from wave energy is still high, but it is forecasted to decrease further with the development of the technologies.

Although early programmes for research and development on wave energy considered designs of several MW output power, recent designs are rated at power levels ranging from a few kW's up to some MW's. Massive power production can be achieved by interconnection of large numbers of devices.

The amount of ongoing development work on wave energy technologies is very large, and cannot be done justice in a single presentation. Here, some of the promising technologies will be presented that have progressed to open sea testing. For ease of presentation the devices are categorised according to the distance of the location of installation from the shore.

4.4 Shoreline Devices

Shoreline devices are fixed to or embedded in the shoreline, having the advantage of easier installation and maintenance. In addition shoreline devices do not require deep-water moorings or long lengths of underwater electrical cable. However, they would experience a much less powerful wave regime. This could be partially compensated by natural energy concentration ("hot spots"). Furthermore, the deployment of such schemes could be limited by requirements for shoreline geology, tidal range, preservation of coastal scenery etc. The most advanced class of shoreline devices is the oscillating water column (OWC). Two of the OWC wave power plants developed in Europe are the following:

4.4.1 European Pilot OWC Plant

Figure 4-5: The Pico OWC pant at the Azores, Portugal [46]

The wave power plant at the island of Pico, on the Azores (PT), is a 400 kW rated shoreline Oscillating Water Column equipped with a Wells turbine. The Pico plant was built between 1995 and 1999, under the co-ordination of Instituto Superior Técnico (PT), co-funded by the European Commission, Figure 4-5. Flooding and malfunction problems affected the commissioning of the plant and delayed the testing programme.

Real sea testing was initiated in September 2005 interrupted by inspection and maintenance, the testing programme being expected to continue in 2007

Based on the experience of the Pico OWC a "wave energy breakwater" project is currently being developed as a commercial approach in Spain and Portugal. The device will be integrated in a caisson breakwater head.

4.4.2 Limpet OWC

The Limpet OWC, developed by WaveGen Ltd. (UK), has been commissioned in December 2000 on the Island of Islay, off the west coast of Scotland, Figure 4-6. The OWC feeds a pair of counter-rotating Wells turbines each of which drives a 250kW generator, giving a name-plate rating of 500kW.

After being in grid connected operation for nearly 2 years the Limpet OWC has demonstrated the capacity of wave generated electricity to contribute to a national grid supply. Both the collector and the turbo-generation equipment have proved robust and have survived extremes of weather with minimum maintenance. This demonstrates that wave energy can be extracted in a low maintenance environment.

Overall the project has been a success as a technology demonstrator, as a platform for testing equipment and as a vehicle for gaining operational experience relevant to both shoreline and offshore generators. The plant will continue to operate supplying the national grid and will serve as a test bed for future power take off systems.

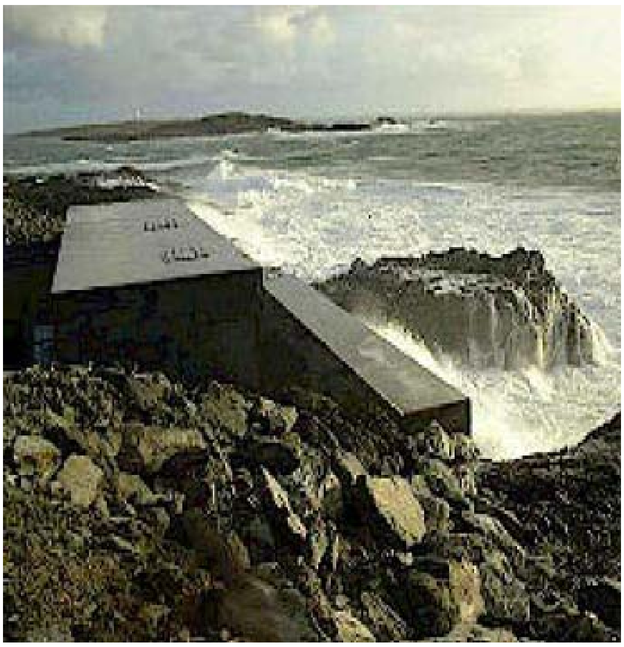

Figure 4-6: The Limpet OWC at the Islay, Scotland [47]

Wavegen and SEV, the Faroese electricity company, are currently jointly developing a wave power station based on a series of OWC-turbine power generation modules. The key innovative feature is the use of tunnels cut into the cliffs on the shoreline to form the chamber which captures the energy. The new design offers a novel and complementary approach to shoreline devices that is well-protected and unobtrusive [7]**Fehler! Verweisquelle konnte nicht gefunden werden.**.

4.5 Near shore Devices

Near shore devices are deployed at moderate water depths (~20 m), at distances typically up to ~500 m from the shore. They have nearly the same advantages as shoreline devices, being at the same time exposed to higher wave power levels.

4.5.1 The WaveStar

The Wave Star, developed by Wave Star Energy ApS (DK), has been commissioned in Denmark in 2006 in scale 1:10 at the test station in Nissum Bredning, Figure 4-7.

Wave Star is based on conventional technology, which consists of well-known offshore technology and wind turbine technology. The basic concept behind Wave Star is fundamentally different to many other wave power models. The machine does not form a barrier against the waves, with a view to harnessing all of their energy, but instead cuts in at right angles to the direction of the wave. In this way the waves run through the length of the machine, and their energy is exploited in a continuous process.

On either side of the oblong machine there are 20 hemisphere-shaped floats which are partially submerged in the water. When a wave rolls in, the first float is lifted upwards, and then the second and so on, until the wave subsides. The floats are each positioned at the base of their own hydraulic cylinder. When a float is raised, a piston in the cylinder presses oil into the machine's common transmission system with a pressure of up to 200 bar. The pressure drives a hydraulic motor, which is connected to the generator, which produces the electricity.

Figure 4-7: The Wave Star deployed at the Wave Danish Test Station, Nissum Bredning [56]

As the machine is several wave lengths long, the floats will work continuously to harness energy. The system is based on a jacket structure, which sits on the seabed and which allows the system to be shut off during storms. During storms all floats are lifted out of the water and are only exposed to wind loads. The system is optimised to operate in relatively small waves, which represents 95% of the annual available energy. In the North Sea it represents an average wave height of app. 1.4 m and a range of wave heights, between 0.5 and 6 m. A section in scale 1:2 is expected to be tested outside the harbour at Hanstholm, Denmark by 2009.

4.6 Offshore Devices

This class of device exploits the more powerful wave regimes available in deep water (>30m depth). More recent designs for offshore devices concentrate on small, modular devices, yielding high power output when deployed in arrays. Some of the promising offshore wave energy converters developed are described in the following:

4.6.1 Archimedes Wave Swing

The Archimedes Wave Swing (AWS), originally developed by Teamwork Technology BV (NL), the rights now owned by AWS Ocean Energy LTD (UK), consists of a hollow, pressurized steel structure, the upper part of which is initiated to heave motions by the periodic changing of hydrostatic pressure beneath a wave, *Figure 4-8*. Being submerged, the device is characterized by low visual and acoustic impact.

Figure 4-8: The AWS in the sea outside Porto, Portugal [48]

Following to numerical and laboratory testing from 1995 to 2003, a 2MW prototype was installed in 2005 offshore Portugal, which was tested for seven months. During this period the system supplied into the 15kV local grid and demonstrated its controls and reliability. The results gave confidence in the direct drive-permanent magnet-linear generator technology employed in the AWS.

The company now focuses on the development of a new model (AWS II), the design of which is based on the experiences with the original AWS. AWS II is a tension leg submerged platform which will not use the fixed pontoon system of the original design. At present the device design is finished and the preparation is started to manufacture and install a pre-commercial demonstrator at the EMEC Centre at Orkney. The rated power will be 1MW and it will be the first device of a wave energy farm. The AWS II is designed to be maintenance friendly needing visual inspection and minor maintenance once in three years, and general maintenance once in ten years.

4.6.2 Pelamis

The Pelamis, developed by Palamis Wave Power Ltd, UK), is a semi-submerged, articulated structure composed of cylindrical sections linked by hinged joints, Figure 4-9. The wave-induced motion of these joints is resisted by hydraulic rams, which pump high-pressure oil through hydraulic motors via smoothing accumulators. The hydraulic motors drive electrical generators to produce electricity. Several devices can be connected together and linked to shore through a single seabed cable. The machine is held in position by a patented mooring system.

In the period 1998 – 2004 Pelamis has been undergone wave tank and open sea testing at scales ranging from 1/80 to 1/7. In 2004 a 750kW commercial-scale prototype was installed at the European Marine Energy Centre in Orkney. The prototype is 120m long, 3.5 m in diameter and contains three 250 kW power modules.

Following to the successful prototype tests, Pelamis signed in 2005 an order with a Portuguese consortium to deliver early 2006 three 750kW Pelamis machines with a combined rating of 2.25MW. The machines have undergone final assembly at Port of Peniche prior to installation 5km off northern Portugal in September 2008. A letter of intent has also been signed to order a further 28 Pelamis machines subject to satisfactory performance of the initial phase. The eventual 22.5MW project will meet the electricity demand of 15,000 households whilst displacing annually more than 60,000 tonnes of carbon-dioxide emissions.

Figure 4-9: The Pelamis at the ship yard in Peniche, Portugal 2007 [49]

4.6.3 PowerBuoy

Figure 4-10: The OPT deployed in the US [50]

The PowerBuoy is a point absorber developed by Ocean Power Technologies (USA). The system uses an ocean-going buoy to capture and convert wave energy into electricity via a patented power take-off. The generated power is transmitted ashore via an underwater power cable. In the event of extreme waves, the system automatically locks-up and ceases power production. When the wave heights return to normal, the system unlocks and recommences energy conversion and power transmission. The PowerBuoy, which utilizes conventional mooring systems, can be deployed in arrays scalable to 100's of megawatts.

Commencing in 1997, the PowerBuoy has undergone ocean testing in the Atlantic and Pacific Oceans. In June 2004 and October 2005 40kW units have been deployed off the coast of Oahu, Hawaii, to demonstrate wave power for use at US Navy bases, Figure 4-10. Another 40 kW demonstration unit was put in operation in October 2005 at Atlantic City, New Jersey.

Early 2006 the company will begin the first phase of installation of a 1.25MW wave farm off the northern coast of Spain. The project is a joint venture with the Spanish utility Iberdrola and it is expected to be operational in 2008. In addition, a full size demonstration plant of up to 10MW capacity is planned for installation in the UK.

4.6.4 Wavebob

The Wavebob, developed by Wavebob Ltd (UK), comprises a wave energy absorber and a hydraulic power take-off system driving synchronous alternators, Figure 4-11. The absorber is an axisymmetric, compound, and self-reacting oscillator operating primarily in the heave mode. The Wavebob is being designed for offshore deployment in large arrays. Commercial units will have a concrete structure floating on compliant moorings with an expected lifetime of 20 years.

Figure 4-11: The Wavebob deployed at Galway Bay, Northern Ireland [51]

The power take-off system of the WaveBob device is modular, safely accessible, and it is designed to have low operating and maintenance costs. Fully autonomous on-board control will facilitate good prediction of power output to the grid. Each Wavebob unit will carry three 0.5MW alternators (giving in total a rated output of 1.5MW) driven at constant speed by hydraulic motors operating off oil pressure accumulators. The preferable depths of deployment are greater than 70m, readily available in the energetic waters of the North Atlantic off Western Europe.

In the past years the concept has been analysed, and the theoretical basis, which comprises frequency and time-domain simulation models, has been verified by independently run tank tests at various scales. A semi-scale (1:4) prototype is currently being tested in Galway Bay in Northern Ireland. One of the aims of these tests is the verification of the time domain modelling approach to explore alternatives, and to test for an optimum device performance.

4.6.5 AquaBuOY

AquaEnergy was formed in USA in 2001 and holds the patents relating to the AquaBuOY technology that combines the hose-pump component of the "Hose-pump project" into the "IPS point absorber system". The AquaBuOY is a slack moored point absorber reacting against a mass of water enclosed in an acceleration tube beneath the float. In the tube is a piston that is forced by the water mass in the tube to move relative to the float. The relative motion activates two hose-pumps (upper and lower) pumping pressurized water delivered to a turbine driving a generator.

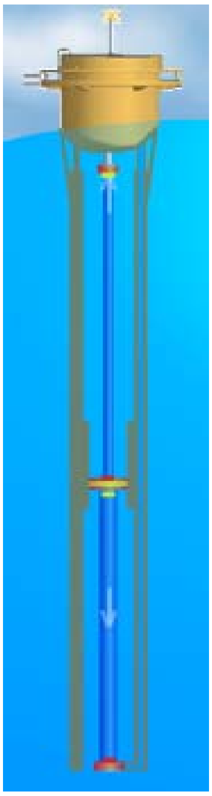

Figure 4-12: The AquaBuOY to be deployed at the west coast of US [58].

A wave power plant will consist of a large number AquaBuOY's interconnected by a high-pressure hydraulic manifold. The manifold employs an open loop of seawater in a hydraulic system. Part of the hydraulic interconnection system provides mooring support between AquaBuOY devices.

The manifold conducts the high-pressure brine to the central multi-jet Pelton turbine converting the high-pressure water to mechanical shaft power. A variable speed electrical generator converts this power to electricity. The housing of the turbine and generator is placed above sea on a platform.

AquaBuOY has October 2007 deployed a prototype at the west coast of Oregon, US.

4.6.6 Wave Dragon

The Wave Dragon is an offshore overtopping device developed by a group of companies led by Wave Dragon ApS (DK). It utilizes a patented wave reflector design to focus the wave towards a ramp and fill a higher-level reservoir. Electricity is produced by a set of low-head propeller type turbines.

From 1998 onwards the performance of Wave Dragon has been optimised through numerical modelling and wave tank testing. The optimisations focused especially on the reflector design and the cross section of the ramp, and have almost doubled the energy capture compared to the 1st generation design. In May 2003, a 57 x 27 m wide and 237 tonnes heavy 1:4.5 scaled prototype was installed and grid connected in Nissum Bredning, Figure 4-13. The prototype is fully equipped with hydro turbines and automatic control systems, and is instrumented in order to monitor power production, wave climate, mooring forces, stresses and device motion.

Recently, Wave Dragon ApS received from the Welsh Assembly Government confirmation for a multi-MW demonstration project. It involves the two stage development, financing, construction and operation of up to 77MW of wave generated electricity in Wales. The first stage of project development comprises the deployment of a 7MW Wave Dragon unit off the coast of West Wales, near Milford Haven by 2009/2010. The unit is projected to provide sufficient electricity to power up to 6,000 homes. A 50MW project is planned for in Portugal by 2010-2011.

Figure 4-13: Wave Dragon deployed at the Danish Wave Test Station, Nissum Bredning [52].

Table 4-1: Technical characteristics of wave power plants.

Type	Name	Load	Type of operation	Country	Currently projected
Wave		kW			year
OWC	Pico	400	Demo	Portugal	1995-1999
OWC	Limpet	500	Demo	UK	2000
Buoy	AWS	2,000	Demo	Portugal	2004
Buoy	AquaBuOY	50	Demo	USA	2007
Buoy	PowerBuoy	40	Demo	USA/Spain	2008
Pitching	Pelamis	750	Demo	UK	2006
Pitching	Pelamis	2,250	Pre-commercial	Portugal	2008
Overtopping	Wave Dragon	2.4	Demo	Denmark	2003
Overtopping	Wave Dragon	7,000	Pre -commercial	UK/Portugal	2009/10

4.7 Present reference systems

To be able to describe technologies and their development paths in quantitative terms (e.g. costs of electricity), it is necessary to specify reference technologies. Within each of the wave technologies like e.g. oscillating water column, buoys, heaving pitching and surging devices, alternative configurations and niche markets exist. To make this abundance of cases manageable, a limitation of alternatives is necessary. The following restrictions are made:

Only devices tested under real sea conditions over longer time has been included. Among these technologies four representative technologies have been included as illustrated in Table 4-2.

Due to economics of scale, wave farms consisting of multiple devices all connected to one transformer station are more economically viable than individual devices. Therefore offshore wave devices are in the future only considered in farms, where multiple devices connected to one transformer station is categorized as one wave power plant.

Table 4.2 shows those technologies to be modelled as reference systems representing the state-of-the art within wave energy. Again, the different stages of development of these reference technologies should be stressed.

Table 4-3: Reference technologies, representing the state-of-the-art of wave power plants.

Type	Name	Rated power
		MW
OWC	Pico	0.40
Buoy	AquaBuOY	0.05
Pitching	Pelamis	0.75
Overtopping	Wave Dragon	7.0

As developers have been very reluctant to release more detailed data for their devices only the device Wave Dragon has been possible to include in the study. Wave Dragon is far the largest device in power. As a power plant it can be regarded as representative even though more of the other devices have another combination of steel and reinforced concrete. Another difference to be taken into account is that the difference in power output will result in larger amounts of cables to give the same power for devices with low rated power.

5 Tidal Energy Power Plant today

5.1 Tidal Energy Physics and Resource

Tidal energy conversion techniques exploit the natural rise and fall of the level of the oceans caused principally by the interaction of the gravitational fields in the planetary system of the Earth, the Sun and the Moon. The main periods of these tides are diurnal at about 24h and semidiurnal at about 12h 25min. During the year, this motion is being influenced by the positions of the three planets with respect to each other. Spring tides occur when the tide-generating forces of the Sun and the Moon are acting in the same directions. In this situation, the lunar tide is superimposed to the solar tide. Some coastlines, particularly estuaries, accentuate this effect creating tidal ranges of up to ~17m. Neap tides occur when the tide-generating forces of the sun and the moon are acting at right angles to each other.

The vertical water movements associated with the rise and fall of the tides are accompanied by roughly horizontal water motions termed tidal currents. It has therefore to be distinguished between:

- Tidal range energy, the potential energy of a tide, and
- Tidal current energy, the kinetic energy of the water particles in a tide.

Tidal currents have the same periodicities as the vertical oscillations, being thus predictable, but tend to follow an elliptical path and do not normally involve a simple to-and-fro motion. Where tidal currents are channelled through constraining topography, such as straits between islands, very high water particle velocities can occur. These relatively rapid tidal currents typically have peak velocities during spring tides in the region of 2 to 3m/s or more.

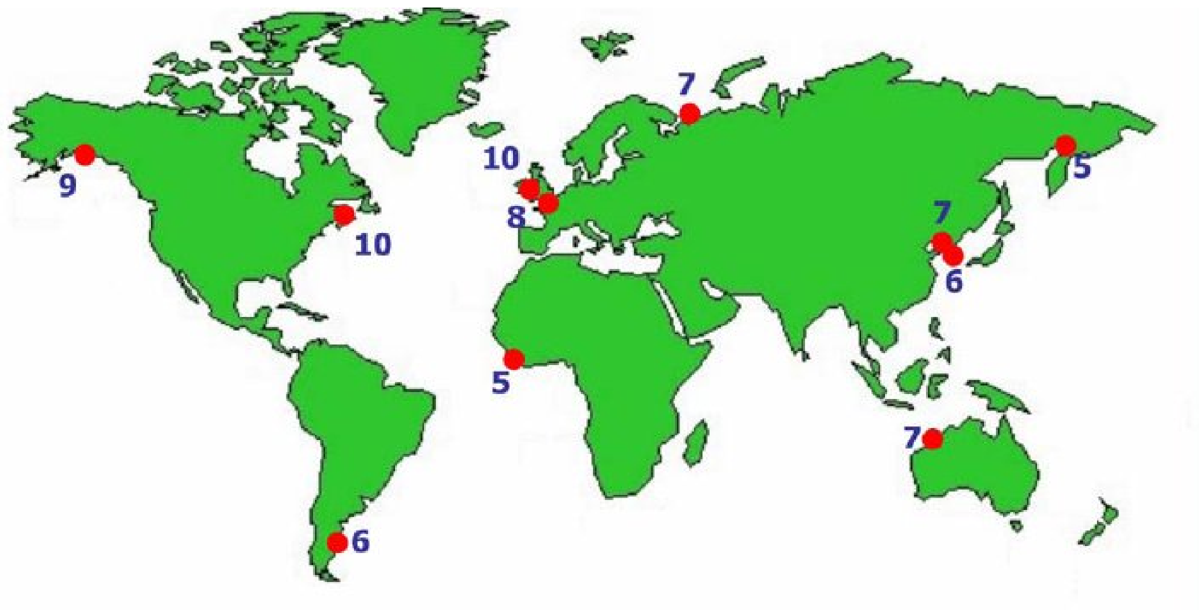

Figure 5-1: The tidal range in meters [2].

Currents are also generated by the winds, and temperature and salinity differences. The term “marine currents”, often met in literature, encompasses several types of ocean currents. Wind driven currents affect the water at the top of the oceans; down to about 600-800m. Currents caused by thermal and salinity gradients are normally slow, deep water currents, that begin in the icy waters around the north polar ice. Wind driven currents appear to be less suitable for power generation than tidal currents, as they are in general slower. Moreover, tidal currents exhibit usually their maximum speed at comparably shallow waters accessible for large engineering works.

The global tidal range energy potential is estimated to be about 3TW, about 1TW being available at comparably shallow waters. Within the European Union, France and the United Kingdom have sufficiently high tidal ranges of over 10 metres. Beyond the European Union, Canada, the CIS, Argentina, Western Australia and Korea have potentially interesting sites, which have been periodically investigated. Some regions with exceptional tidal range are shown on *Figure 5-1* (annual average tidal range in meters).

Recent studies indicate that marine currents have the potential to supply a significant fraction of future electricity needs. The potential for marine current turbines in Europe is estimated to exceed 12,000MW of installed capacity. Locations with especially intense currents are found around the British Islands and Ireland, between the Channel Islands and France, in the Straits of Messina between Italy and Sicily, and in various channels between the Greek islands in the Aegean. Other large marine current resources can be found in regions such as South East Asia, both the east and west coasts of Canada and certainly in many other places around the Globe that require further investigation.

5.2 Principles and Aspects of Tidal Energy conversion

5.2.1 Tidal Range Energy

The technology required to convert tidal range energy into electricity is very similar to the technology used in traditional hydroelectric power plants. The first requirement is a dam or "barrage" across a tidal bay or estuary. At certain points along the dam, gates and turbines are installed. When there is an adequate difference in the elevation of the water on the different sides of the barrage, the gates are opened. The "hydrostatic head" that is created, causes water to flow through the turbines, turning an electric generator to produce electricity.

Tidal range energy conversion technology is considered mature, but, as with all large civil engineering projects, there would be a series of technical and environmental risks to address. One major environmental risk is associated with the changes of water levels which would modify currents, and sediment transport and deposit. However, there are regional development benefits as well, for example the La Rance plant in France, the only commercial sized tidal range conversion scheme so far, includes a road crossing linking two previously isolated communities and has allowed further development of the distribution network for raw materials and developed products.

5.2.2 Tidal Current Energy

Tidal currents can be harnessed using technologies similar to those used for wind energy conversion, i.e. turbines of horizontal or vertical axis (“cross flow” turbine). Some other techniques have either been abandoned or are at an early stage of development.

Several types of tidal current conversion devices, particularly fully submerged devices, are subject to the corrosive effects of seawater. This leads to high material and construction costs. In addition, maintenance is difficult because divers are needed to access submerged machinery. While placing the drive train above water can minimize the need for divers, maintenance costs would remain higher than e.g. in wind turbines.

In contrast to atmospheric airflows the availability of tidal currents can be predicted very accurately, as their motion will be tuned with the local tidal conditions. Because the density of water is some 850 times higher than that of air, the power intensity in water currents is significantly higher than in airflows. Consequently, a water current turbine can be built considerably smaller than an equivalent powered wind turbine.

Another specific advantage of tidal current devices is the limited environmental impact. Their installation requires minimal land use, and fully submerged devices will not affect optically or acoustically their surroundings. Their effects on flora or fauna have not been studied extensively yet, but it is unlikely that they will be of significance. Finally, submerged marine current converters are considered to operate in safe environment: disturbances caused by extreme weather conditions are significantly attenuated to the depths of about 20-30 metres where the devices will normally operate.

5.3 Tidal Energy Development Status

Tidal energy conversion is being investigated in a limited number of countries, particularly in the member States of the European Union, China and Korea. In the following a summary is given.

5.4 Tidal Range Energy

Tidal range energy projects require normally high capital investment at the outset, having relatively long construction periods and long payback periods. Consequently, the electricity cost is highly sensitive to the discount rate used. Access to suitable funding is thus a serious problem, and is unlikely without public intervention.

The first large scale, commercial plant was built on the Rance estuary in France during the 1960's and has now completed over 40 years of successful operation. The La Rance station is still the only industrial-sized tidal power station worldwide [57]. Its 240 MW power is about 1/5th of an EDF (Electricité de France) nuclear reactor and is more than 10 times the power of the biggest among the other tidal stations in the world.

The good performance of La Rance has resulted in examination of additional projects in France, which was finally abandoned because of their high investment costs and environmental concerns. Various other smaller plants have been built in Russia, Canada and China. In the UK a series of industrial consortia have investigated the prospects for tidal energy on the Severn, Mersey and a number of smaller estuaries.

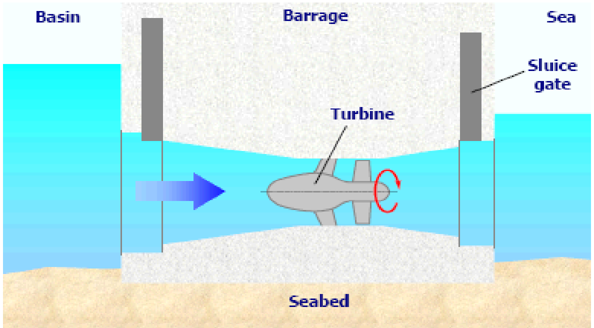

Figure 5-2: The 240MW tidal range plant in La Ranche, France [2]

The comparably high generation costs and long payback periods of shoreline tidal range schemes imply that within deregulated electricity markets, which are based on private investment, tidal energy is unlikely to be commercially developed, if the kWh price does not become competitive to cost-effective renewable energies. The development of offshore tidal range energy could resolve many of the financial and environmental constraints of shoreline tidal range energy.

5.5 Tidal Current Energy

Tidal current technology is in its infancy. Recent developments open up prospects for commercial deployment of some schemes in the near future. The economical viability of these schemes is proven yet, but it is anticipated that the production costs will decrease as the technologies advance. At present, different pilot plants are in operation or about to be installed, mainly in Europe. Most devices rely on the horizontal or vertical axis turbine concepts.

5.5.1 Kobold

The Kobold device, developed by Ponte di Archimede SpA (IT), is a vertical axis tidal current turbine. Its development started in 1995 based on the concept for a simple and reliable current converter.

The device employs a patented, vertical axis rotor driving a synchronous generator. An important feature of the Kobold is that the direction of rotation of the rotor is independent of the current direction.

The Kobold device was optimised by numerical modelling and towing tank testing with a 1:4.5 scale model. In 2002 a prototype was deployed in the Strait of Messina and it continues since then grid connected operation, *Figure 5-3*. The plant is positioned about 150 – 200m from the shore. The depth ranges from 15 to 35m and the maximum current speed is around 2.0m/s although there are places in the Strait of Messina where the current speed can be more than 3.0m/s.

Figure 5-3: The Kobold tidal current demonstration plant in the Messina Strait, Italy [54].

The rotor has a diameter of 6m and consists of three blades with a span of 5m each. It drives an alternator through an epicycloidal overgear. The system is mounted on a floating steel platform of 10m diameter. The platform is moored to the seabed by means of four mooring lines.

The tests indicate that the turbine produces 25kW of power in a current speed of 1.8m/s. In a current of 3.0m/sec 80kW are expected. The device is equipped with a photovoltaic roof which is parallel connected to the local grid.

5.5.2 SeaFlow, Seagen

The SeaFlow device is developed by Marine Current Turbines Ltd. (UK). The device consists of a horizontal axis rotor mounted on a steel mono-pile set into a socket drilled in the seabed.

Figure 5-4: The SeaFlow demonstration plant near Devon, UK [53]

Preliminary development work was carried out in the period 1999 – 2002 and included open sea tests with a 15 kW unit with a 3.5 m diameter rotor. In 2003 a prototype was successfully installed and commissioned 1km off Foreland Point, near Devon, UK, at a depth of 30m, *Figure 5-4*. The device has a rotor of 15 m of diameter and it can generate a maximum of 300kW in a 2.7m/s current. A key patented feature of the technology is that the rotor and drive train can be raised completely above the surface for maintenance.

The SeaFlow device has meanwhile passed a period of 3 years of operation confirming the technical viability of the concept for mono-pile mounted tidal turbines. Recent work has involved automation of operation and measurements relating to environmental impact, including underwater noise measurements and wake measurements to determine the turbine's "footprint" in the tidal flow.

In 2006 the company received permission to install at Strangford Lough, Northern Ireland, SeaGen, a 1.2MW "twin-rotor" tidal current device, which will confirm the potential for commercial success of the technology. The device has been grid-connected in the autumn 2008 and will function with the flow in both directions. The company also explores the feasibility of building a 10 MW tidal farm with 12 units off Foreland Point on the north Devon coast and another project at the Welsh coast.

5.5.3 Tocardo

The Tocardo device, which is developed by Teamwork Technology BV (NL), is a horizontal axis marine current turbine, *Figure 5-5*. It is designed for installation in the exhaust flumes of the various storm barrages in Holland.

The present design, which evolved from comparison of different methodologies, is conventional, using a two bladed, fixed pitch, variable speed rotor of 2.8 m diameter and a gearbox. A first unit was tested in Holland in an exhaust flume in 2006 where during low tide the water from the IJselmeer in the Netherlands flows into the North Sea with max. water velocity of

4.5 m/s. The device is rated with 35kW at current speed of 3.2 m/s. During the demonstration period electricity was supplied to the grid.

Figure 5-5: The Tocardo demonstration unit, IJselmeer, The Netherlands [55]

The device control is adaptive, in which the system finds its optimal flow/ rotation speed ratio automatically. In the commercial series the gearbox will be replaced by a direct drive permanent magnet generator. The lifetime of the device is estimated at 25 years, with a need of overall maintenance only every ten years.

The first commercial applications of the turbines will be in existing storm barrages that are in the Netherlands at several places. Together with the ongoing project for the installation of three systems in the Netherland by November 2006, a study to install ten systems in the Oosterschelde dam is performed, the capacity of which is estimated to at least 100 – 200MW.

5.6 Summary

Table 5-1 summarises the technical data described so far of the state-of-the-art for the wave and tidal reference technologies.

Table 5-1: Technical characteristics of tidal power plants.

Type	Name	Rated power	Type of operation	Currently projected
Tidal		MW		year
Barrage	La Rance	600	Commercial	1966
Barrage	Nova Scotia	20	Commercial	1984
Current	MCT	0.5	Demo	2003
Current	Seagen	1.2	Pre-Commercial	2008
Current	Kobolt	0.025	Demo	2002

5.7 Present reference systems

To be able to describe technologies and their development paths in quantitative terms (e.g. costs of electricity), it is necessary to specify reference technologies. Within each of the and tidal technologies only few alternative configurations and niche markets exist. To make this abundance of cases manageable, a limitation of alternatives is necessary. The following restrictions are made:

Only devices tested under real sea conditions over longer time has been included.

Table 5.2 shows those technologies to be modelled as reference systems representing the state-of-the art within tidal energy.

Table 5-2: Reference technologies, representing the state-of-the-art of tidal and current power plants.

Type	Name	Rated Power
Tidal		MW
Barrage	La Rance	600
Current	Seagen	1.2

The tidal barrage type is not judged as representative for the tidal development in the future as this kind of tidal device is closely dependent of the need for an infrastructure like a dam or a bridge. The energy economy can only be justified in combination with a combined assessment including the infrastructure.

Seagen (MCT) is therefore the only device to be used as representative for tidal current technologies. It has not been possible to get data from the developer MCT and therefore this kind of device cannot be included in the study except for data related to LCA, see chapter 9.

6 Wave and tidal power technology development road map

6.1 General political framework

The general political development in the next decades is an important determinant of the deployment of the energy system of the future. The political framework will influence main technological drivers or even introduce or enforce them. It will thus have an influence on the future role of the various power technologies.

The following general political objectives will presumably be the guidelines for the energy system development in Europe in the next five decades:

- Provision of electricity at an economically justifiable price level,
- Security of supply (making demands on back-up capacities and treatment of fluctuating energy sources as well as on the import of fuels and electricity),
- Near-to-zero emission technologies as benchmark (regarding mainly greenhouse gases, but also SO_2, NO_x, particulates), and
- Minimisation of social risks caused by energy technologies (e.g. proliferation-prone nuclear technologies), high social acceptance of the used energy technologies.

In 1997 the White Paper on Renewable Sources of Energy [22] set the target for doubling of the use of renewable energy in the EU from 6% by 1997 to 12% by 2010. This was followed by the Renewable Energy Directive [23] from 2001 with the target to increase the EU share of electricity based on renewable energy sources from 15% by 2001 to 21% by 2010.

January 2008 a new directive was announced and agreed aiming for 20% renewal energy by 2020 [24].

When looking at target specifically dealing with wave and tidal energy the only EC document today is the SET plan [25] in which opportunities of 5-10GW by 2020 and 15-25GW by 2030 is mentioned.

National targets are known recently from Ireland, Portugal and Scotland [27], [31], and [32].

Table 6.1 Countries with specific targets related to the future use of wave and tidal energy

Country	Energy source	2010-2012	2020
Ireland	Ocean energy	75MW	500MW
Scotland	Ocean energy	-	700MW
Portugal *	Wave energy	-	330MW
Basque Country	Wave energy	5MW	-

* Based on maximum capacity for demonstration zone

6.2 Drivers and barriers

Drivers are developments/events/institutions, which influence a technology by pushing or inhibiting its development. The word “driver” thus is not only meant in the sense of “driving force”, but also in the sense of an obstructing force or barriers. The following drivers are partly of general nature and common for almost all renewable energy sources and partly wave and tidal specific.

Objective of long-term economically viable electricity prices

Electricity is an indispensable good for developed economies and societies. An affordable price of electricity is an extremely important factor to their further preparation. The ongoing rise of fossil fuel prices [59] may thus reveal to be the most important driver for wave and tidal technologies: High shares of wave and tidal power means a long-term decoupling from the fossil energy prices. Anyway, a general rise of electricity prices in the next decades cannot be avoided due to remaining high fossil shares in the electricity mix combined with an assumed increased prise of fossil fuel. But the enforced deployment of wave and tidal capacities means a substantial contribution to long-term affordable electricity prices.

Objective of security of supply

Security of supply has two dimensions: On the one hand the technical design of the energy system like choice of technology, back-up capacities, and grid patterns e.g. influences the reliability of the electricity supply. On the other hand a high degree of dependency on fuels and electricity import leads to a risk for an unstable price and reliable electricity supply in Europe.

The objective of security of supply is a pushing factor for wave and tidal energy.

In European countries, which today are highly dependent on fossil fuel imports and has attractive wave climates like e.g. Ireland, UK, Spain or Portugal, wave energy is a high potential source for diversifying energy sources and increasing the share of domestic energy supply.

Climate Protection

The global political demand to reduce CO_2-emissions from the power sector leads to an ongoing internalisation of the costs of CO_2-reduction into the costs of electricity through the expenses on CO_2-certificates. This privileges wave and tidal power generation as CO_2-neutral technologies. Instruments like the Clean Development Mechanism (CDM) envisaged by the Kyoto Protocol over-proportionally push wave and tidal power technologies as CDM allows for making use of excellent sites for wave and tidal energy in developing countries like South Africa and Chile and the respective CO_2 reduction potential in Europe. This directly can influence the time span in which competitiveness for wave and tidal power plants is achieved.

Enforced direct market support for renewable energies (feed-in-laws)

The establishment of preferential market system for renewable energies in several countries world-wide (e.g. feed-in laws in Spain and Germany or the renewable energy certificates (ROC) in UK) and obvious consequential success stories like the wind energy expansion in Spain turns out to be an important driver for wave and tidal power plants. Portugal, UK and Ireland were the first countries to include wave and tidal technologies explicitly into their support schemes. As a result, the first full-scale demonstration plants have been or are expected to be set-up in these countries.

R&D spending

The quantity of funding for wave and tidal research directly and proportionally determines the speed of cost reduction of these technologies (Carbon Trust, UK [18]). On the one hand the speed of technical innovation is not determined; on the other hand the technological challenges of scale-up take time. The R&D volume is a driver strongly influenced by political forces on the national and super-national level. It can be pushing or inhibiting, depending on the volume and the continuity of spending.

Very high potentials worldwide

On the global scale the technical potential of wave and tidal power generation is 5 times the world electricity consumption. Taking the distance to shore into account (strongly influencing the cable cost) the easy achievable potentials for wave and tidal energy is of the same magnitude as the consumption of electricity [1], [2], [3], [29].

Sea use competition in highly populated countries

Wave and tidal energy has a need for a considerable sea area; typical figures of the needed area/MW are 0.03 to 0.05 sqkm/MW. But there are plenty of areas available for the purpose without disturbing ship lanes and fishing grounds. Compared to offshore wind today this demand for area is about 75% but a comparison is in fact not really relevant as offshore wind developers prefer shallow water and most wave developers prefer deep water.

Aiming at conflict neutral technologies

Most energy supply and conversion technologies imply problems concerning environmental, societal and security issues.

The fossil fuel energy supply system is increasingly involved in military conflicts and dependent on instable political environments. Wars have been fought for oil (Iraq) and natural gas is in still higher degree originating from politically unstable areas, affecting the security of supply.

Nuclear energy technologies are subject to an intensive discussion about the allegation that countries in politically instable environments (Iran, North Korea) in the last years have shown an enforced interest in nuclear development.

Large-scale hydropower projects can imply problems with the local flora and fauna, release of methane and societal problems with local migration and loss of agricultural land and even regional security problems regarding the management of water as a resource.

Wave and tidal plants represent more conflict resistant technologies. They do not incorporate conflict relevant materials and even more important, the “fuel” is free, abundant and inexhaustible, and thus won’t cause conflicts to appear.

Increasing demand for local added value

Many countries put more and more emphasis on local added value in investment decisions. They recognize the employment of national/domestic labour force, the accumulation of local expertise and a high degree of national supply as a value for development. Wave and tidal power stations are technologies with a high potential for local added value, especially within civil and mechanical engineering. They have a little fraction of high-tech components, and a large part of the investment is used for steel, concrete, and labour.

Potential for technology export from Europe

The current distribution of industrial and scientific knowledge about wave and tidal technologies are concentrated in Europe just as Europe has the lead in setting up demonstration plants. This will probably bring about export of special components and knowledge from Europe and thus be a pushing factor for further development.

Short-term objective of least costs of electricity

Developing or transitional countries have very limited financial resources for technological investments. Their policies hence enforce investment in technologies offering the lowest costs of electricity in the very short term. External, indirect and non-economic arguments like environmental or long-term arguments are thus difficult to include in the choice of technology. This discriminates against investment into e.g. the wave and tidal sector as this means higher investment in the short-term for the sake of long-term benefits. In countries with high emphasis on current economic least-cost options there is an important market barrier (negative driver) for wave and tidal technologies.

Preferring non-intermittent electricity suppliers

Energy sources with low intermittency means an economic advantage. Wave and tidal technologies will be able to offer a less intermittent energy source than e.g. wind, as its power production is predictable many hours and days ahead **Fehler! Verweisquelle konnte nicht gefunden werden.**[14], [35], [36], [38].

Advanced side applications and side products

Besides electricity generation, which is solely considered this far, wave and tidal technologies have the ability to produce other energy related products/services like e.g. hydrogen, desalination of seawater and growing seaweed and algae for biomass utilisation [14]. The joint production of these side products can widen the market for the core product electricity and thus push the development. The most important applications are the following:

- Hydrogen production in situ based on seawater using the power generated far offshore. The hydrogen can subsequently be transported like LNG.
- Desalination of seawater. Fresh water provision meets pressing demand on many islands and in arid countries and can be produced with osmotic membrane technologies using the ocean power to provide the pressure.
- Biomass based on seaweeds and algae can expand the shore-based production of biomass for food, and energy.

Legal and administrative practise

From the offshore wind sector it is well known [33] and [34] that it is essential to introduce the “one-stop-shop-procedure” (only one entrance to all government bodies in order for the developer not to be a piece in internal disagreement fights). Further on it is known from the Danish and UK deployment of offshore wind sector that a simplified planning regime in the early stage of development is essential for a fast deployment of new technologies like wave and tidal energy.

Ireland, Portugal and the USA have introduced simplified rules [15] and [27].

Financial, risk

Wave and tidal energy requires as most other renewable energy sources more capital upfront than fuel based electricity producing systems. Stable investment conditions and security for long term revenue streams based on the electricity produced is therefore essential.

Scaling up from the research phase is a specific problem related to wave and tidal energy as wave devices have to be scaled to the actual sea (wave length, period and height) which together with the different scaling factor for power (to the power of 3.5 of the scaling factor) is creating problems with finance bodies simply not understanding the physical laws covering wave devices[1].

Technical

The main technology barrier is related to the immature state of the technology. Only two pre-commercial devices within wave and tidal energy have been established by 2008. The remaining many devices are under development or in the beginning of the full scale demonstration phase [5].

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[1] At the Danish test site Nissum Bredning the wave climate is 1:4.5 of the wave climate of the North Sea resulting in a power scale 1:200 (a 20kW device is modeling a 4,000kW device)

Lack of access to grid connection is as known from offshore wind a key barrier in many countries. This is a problem at the very good wave sites at western Ireland and Scotland a key problem for a fast development of wave energy; where it is easier in Portugal and northern Spain where the population is living close to the coast with good wave climate.

Integration into the grid is not expected to be the same barrier as for offshore wind as wave and tidal energy is predictable several days ahead without risk of having abrupt decreases in the power delivered.

6.3 Environmental impacts

Generally, wave and tidal energy is considered a clean, safe and environmentally sound technology. Nevertheless, there are some environmental impacts associated with utilising wave and tidal (ocean) energy technologies, which has to be addressed. These environmental externalities can have an either direct or indirect impact [1], [10], [15] and [27].

6.3.1 Direct environmental impacts from offshore wave energy

A LCA study (on Wave Dragon) has demonstrated that the environmental impacts from manufacturing, operating and decommissioning an offshore wave energy device are negligible compared to those from, for example fossil energy technology [11], [21], [43], [44]. This study revealed that the manufacturing stage is crucial for the overall environmental impacts of the wave energy device, which impacts are aggregated in Figure 6.1. This means that the provision of the materials used for the manufacturing of the wave device and the subsequent disposal of the plant, at the end of the lifetime, are the dominating stages for the environmental impacts from a wave energy device. Therefore it is very important to choose the right materials during the design phase of a wave device and to consider their re-usability in the disposal stage. Unlike the fossil energy technology, the impact during operation is negligible. The LCA item is dealt with in more details in chapter 9.

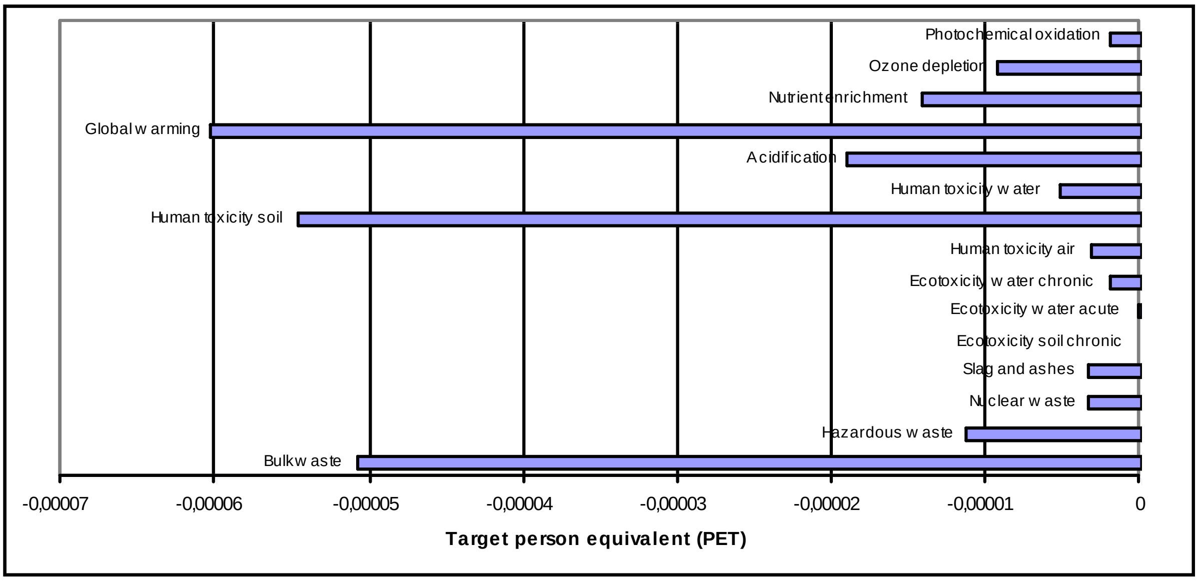

Figure 6-1: Weighted environmental impact potentials for the whole life cycle. The functional unit is defined as one kWh [11].

6.3.2 Externalities associated with wave energy

There are only a few studies on externalities associated with wave energy and all of them are based on predictions as no follow up program has been carried out until now [10]:

- Socio-economic environment. Generally the socio-economic impacts caused by wave and tidal energy are considered to be relatively positive [12], [13], [15] due to the fact that the offshore wave and tidal energy technology produces clean energy/power with only low emission of green house gases throughout its life cycle. Using locally available sources of energy is also extremely important in an area like Europe, which is heavily dependent on oil and gas. The manufacturing, transporting, installing and operation of wave and tidal farms generates/offers employment to the people often living in remote low employment areas. The wave and tidal power production has also some negative socio-economic impacts, such as possible loss of income for the local fishing industry or just a change in methods, catch etc. The existence of underwater cables around the wave farms usually prohibits trawl fishing, but other kinds of fishing are possible.
- Impacts on coastal and seabed processes. The installation process as well as the permanent presence of wave and tidal farms and their cables could have some effect on the coastal and the seabed processes in the vicinity of the ocean energy farms. It is considered that the developments have some localised impacts on waves, currents and the corresponding sediment transport regime in the immediate vicinity of the wind farm structures and callings but it is unlikely to have any significant or measurable far field impacts [15].
- Impacts on the marine environment. The potential effects on the marine environment have been evaluated in many years in the offshore wind technology and can be expected to be of the same nature except for birds. Taking the experience from offshore wind [16] the following impact can be expected:
    - *Infauna and hard bottom substrate:* where new species can be introduced in the wave and tidal farm area. The occurrence of new species might be a result of changes in sediment characteristics. Others may be a result of the introduction of hard bottom habitats in the area. Or it could be due to fact that the wave and tidal farm sites are no longer being used by fishermen.
    - *Fish:* where some of the results of investigation in Danish off shore wind farms sites indicate that the offshore wind farm attracts fish beyond a distance of 500 metres. A significantly higher density of fish in connection with turbine foundations (hard bottom substrates) was found in some of the studies. Similar impact can be expected from wave and tidal devices.
    - *Sand eels:* where there is no indication that the construction of the wind farm areas has had a negative effect on sand eels in these areas. Studies have shown that there was no indication of an increase in the content of silt/clay and very fine sand in the impact area. Furthermore, there was no indication of a decrease in densities of sand eels (all species combined) in the same area. Similar impact can be expected from wave and tidal devices.
    - *Marine mammals* where no studies indicate that seals or porpoises are influenced by the offshore wind activities. Similar impact can be expected from wave and tidal devices.
    - *Bird distribution:* can only be imagined disturbed during commissioning and decommissioning of the wave and tidal farms. Platforms, buoys etc. might

serve as resting positions extending the range of the bird fourage. Similar impact can be expected from wave and tidal devices.

- Alterations to physical environment. The presence of wave and tidal farms in the offshore farm area can enhance the risk of ships colliding with the devices resulting in oil leaks. The risk is considered to be minimal. On the contrary structures can enforce awareness of shallow grounds due to better visibility or radar contact leading to less grounding of ships. (Like it appears be the case with Middelgrunden wind farm outside the harbour of Copenhagen [17]).
- Noise & visual impacts. Negative effects connected to noise from wave and tidal farms are not expected to cause negative impact. The farms are usually placed far from the coast and hence their feasibility and noise propagation are not noticeable onshore. Nevertheless, the noise from the shore based wave devices of the OWC type is known to need mitigation round the turbine in-/outlet. Construction activities like hammering or driving of piles can cause permanent damage to some animals residing in the vicinity.

6.4 Summary of drivers and barriers related to wave and tidal energy

Table 6-1 gives a survey of all the mentioned drivers and their direction of impact. The number of pushing influences is in the majority. Tidal barrage is not included in this table. The impact for this technology is quite difficult to assess and will be different for the other forms of wave and tidal energy.

Table 6-1: Influence of drivers to wave and tidal power technologies

Driver	Onshore	Offshore	Tidal
Guaranteeing economically viable prices	↑	↑	↑
Guaranteeing security of supply	↑	↑	↑
Climate protection	↑	↑	↑
Enforced direct market support (feed-in-laws)	↑	↑	↑
R&D spending	↗	↗	↗
Very high potentials worldwide	↗/→	↑/↗	↗/→
Sea use competition	↓	↘/→	↓
Aiming at conflict neutral technologies	↗	↗	↗
Increasing demand for local added value	↗	↗	↑
Potential for technology export from Europe	↗	↗	↗
Short-term objective of least costs of electricity	↘	↓	↓
Preferring non-intermittent electricity suppliers	↗	↗	↑
Advanced side applications and side products	↑	↑	↗
Restricted production capacities for wave and tidal	↓	↓	→
Other environmental impacts	↘	↗	→
Development in perception and network building	↗	↗	↗

↑ strong pushing driver ↗ pushing driver → small impact or unclear influence ↘ Inhibiting driver ↓ strong inhibiting driver

7 The anticipated role of Wave and Tidal energy in a future energy supply system

A number of organisations, institutions and authors have produced roadmaps or forecasts for the role of wave and tidal energy in the future energy mix, see next section. While some of these forecasts are projections based on detailed analysis others should be considered as political strategy targets.

The wave and tidal energy industry is only in its infantry and just in September 2008 the first pre-commercial wave farm consisting of 3 units each 750 kW was deployed of the west coast of Portugal. The first pre-commercial tidal device with a rated power of 1.2MW was grind connected in the autumn of 2008.

Therefore predictions for a distant future like 2050 will be rather uncertain. On the other hand the wind industry can be used as a reliable case study with the following exceptions:

- In general wave devices have to be tested in scale 1:1 caused by the dependence of wave period, length and high. The development of prototypes therefore takes place using wave tanks for scale 1:50 and in downscaled sea in scale 1:5 before a scale 1:1 is tested in the actual sea.
- When a wave energy device has been deployed successfully in open sea in its intended size, it can be duplicated without any significant changes for a long period. The only modifications are an adjustment to the variation is sea state.
- Electricity produced based on wave and tidal devices are much more predictable than wind energy (several days for wave energy and years for tidal energy).

An increase over 25 years as has been seen in the wind industry from the early 25kW devices to to-days 2-5MW devices will not take place [40].

The development path for wave energy is therefore first and of all dependent of the price compared to competing technologies. The price of the wave device is a function of:

- Mass production/economy of scale production
- Savings in costs introducing multiple manufactures and developers in the offshore market.
- Increase in production introducing multiple operators.

These decreases in price of the wave and tidal energy are expressed by the learning curve experience [42].

The information available for this NEEDS project from the different developers unfortunately has been very restricted. The following chapters are based mainly on information related to wave energy based on the information delivered by the developer Wave Dragon. This technology with a rated power of 4 to 12MW is 10 to 15 times larger than the rated generator capacity of the other wave developer at the same stage of development: Pelamis and is anyway regarded as representative as illustrated in Chapter 10.

7.1 Projections for wave and tidal energy

During the last 10 years several projections for wave and tidal energy have been suggested.

In a report to World Energy Council 2001, [29] a range from 1 - 10TW was mentioned which with a load factor of 40% equalize 25 - 200% of the worlds electricity consumption (2005). A realistic technical achievable potential was mentioned as 50%.

In a report to the European Commission a realistic potential of 2,000TWh/year was mentioned 2002, [1].

The recent Survey of Energy Resources from WEC 2007, [63] these figures are maintained.

In a report to the IPCC 2008, [3] a potential of 8,000 - 80,000TWh/year of wave energy and 2,000TWh/year of tidal energy is mentioned.

Table 7-1 gives an overview about the different deployment scenarios from IEA [64], Carbon Trust [8] and EREC/Greenpeace [28], [65].

Table 7-1: Scenarios of installed capacity deployment from existing studies

All values in GW	2010	2020	2030	2040	2050
IEA		52			
Carbon Trust					200
EREC/GP 2007 2%	2	14	28	46	63
EREC/GP 2007 BAU	0	2	3	4	4
EREC/GP 2008 2%	1	17	44	98	194
EREC/GP 2008 BAU	0	2	4	7	9

Different countries and regions have given projections as follows:

In the EU SET-Plan, [25] a European potential of 150-240TWh/year is mentioned. For 2020 an installed capacity of 10GW by 2020 and 16GW by 2030 is anticipated.

In the British projections a potential of 3GW is mentioned by 2020. In a Carbon Trust report a potential of 200GW by 2050 worldwide is mentioned.

7.2 What can be reached? – Development targets for 2050

In the following a possible path of development for wave and tidal technologies to 2050 is described. The path reflects targets of development, which seems realistic. It neither means that the future will necessarily be the way as described nor is it meant a prognosis. It just gives an outline of what is achievable and in the same time aspired.

It is assumed that wave and tidal power plants by 2050 is full economic and technical competitive in the mid-load in the base load sector taken Europe as the supply market. As costs of electricity for wave and tidal technologies varies from site to site, the aim for 2050 is to reach a cost level, where the sites with competitive conditions in Europe and around the world yields an amount of power generation at a level as wind energy a few year ago (1% of electricity supply).

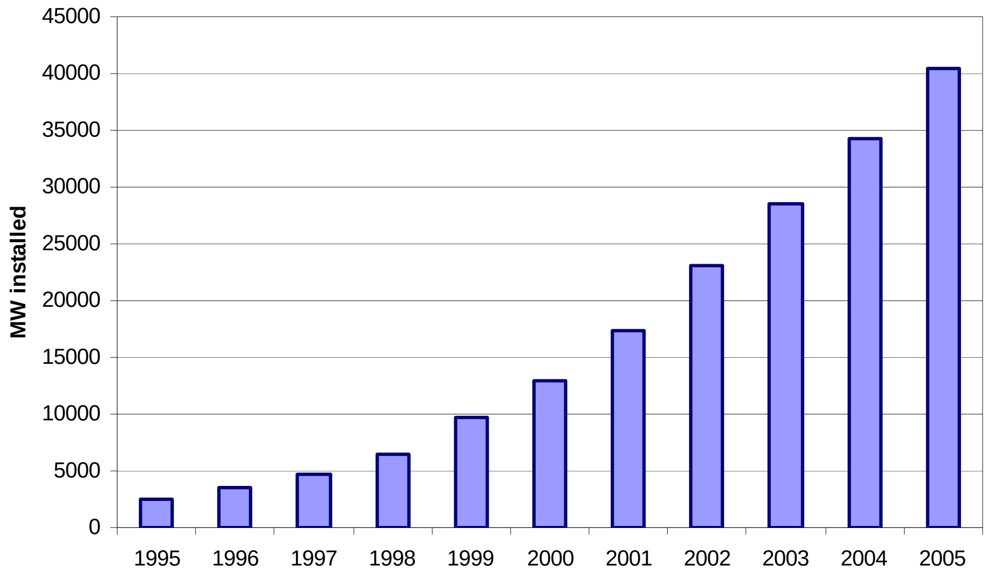

Figure 7.1: The growth of Wind energy installed across Europe [26]

A similar development is expected in the British development scenario [62] as can be seen from Figure 7.2.

Three main phases can be expected:

- The first phase (*activating phase*) is covering the period up to 2015 dealing with pre-commercial development of minor wave and tidal farms. The period is followed by
- The second phase (*building up phase*) is the time until commercial competitiveness is gained.
- The third phase (*competing phase*) is the phase of participating in the electricity market at competitive conditions taking full value of the externalities related to fossil fuel into accounts.

In the scenario description the turning point between the two last phases is anticipated to be 2025 or later depending of the encouragements and achievements in the first period.

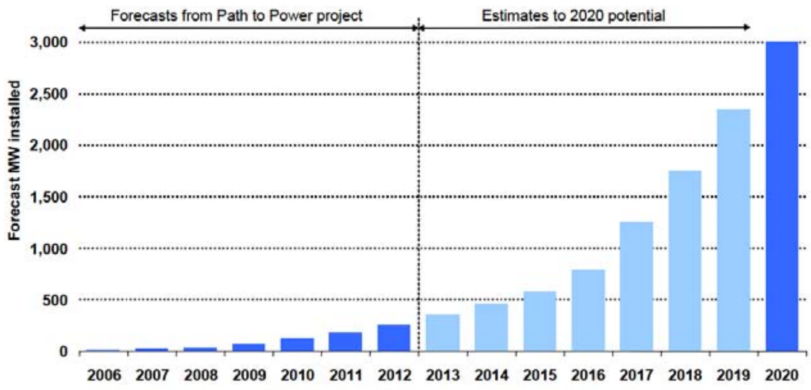

Figure 7.2: Deployment scenario for wave and tidal energy in UK [62]

Stimulating research and development spending near to commercialisation (demo-types) is an important instrument during the first phase. In the *building up phase* a significant increase in R&D efforts is required if the cost reductions which are possible should be realised.

The developments for the two last phases have very different characteristics. The key drivers for the third phase (*competing phase*) will presumably be a "self-runner" meaning that commercial investors will have a strong incentive to invest in wave and tidal plants projects once economic competitiveness has been achieved. Then the process gets self-reinforcing: The more capacity is build the cheaper the technology will get. This dynamics could be a driving factor reducing the influence of external drivers. There are strong arguments that the third phase will follow the same development path as has been seen in the wind industry as illustrated in Figure 7.1. The third phase could even go faster than seen in wind energy as the final size of wave devices is in place from the very beginning[2].

The second phase (*building up phase*) is characterized by a need of incentives beyond what is justified alone by the externalities related to competing energy sources like fossil fuel in order for the manufactures to build up production facilities for mass production. This is a development very similar to what has happened in the wind energy sector.

To achieve a development as described above, pushing of wave and tidal technologies is necessary to reach a critical mass.

A reduction of the subsidies granted for fossil and nuclear power plants will indirectly support wave and tidal energy enabling an electricity market under competitive conditions.

7.3 The three NEEDS scenarios

In the NEEDS project, three scenarios for the future development of the technologies should be presented. It is beyond the scope of the technical working groups in RS1a to define scenarios that are consistent with the same model and coordinated between the working groups. Each working group will therefore select their own models and define three scenarios that are consistent with the following headlines:

- Very optimistic development
- Optimistic-realistic development
- Pessimistic development

[2] The wind energy development went from 25kW turbines to 2-4MW turbines during the first 25 years of development.

Table 7.2: Instruments influencing the development speed of wave and tidal energy

Instrument	Scenario		
	Very optimistic	Optimistic-realistic	Pessimistic
Feed-in-law	******	*****	***
Power purchase agreements	******	*****	***
Reducing subsidies for fossil and nuclear power plants	******	***	*
Increasing fossil fuel prices	******	*****	***
Internalisation of the costs of CO_2 reduction	******	***	*
Clean Development Mechanism	******	***	*
Research and development spending	******	***	**

The number of stars represents the intensity of a measure.

The **very optimistic scenario** is bases on the assumption that both phases the two first phases described in the previous section can fully be explored. Especially in the first phase the maximum of effort has to be activated by all instruments discussed in Table 7.2 to enable an early increase of wave and tidal power plant's capacity. This means that a worldwide and ambitious long-term oriented climate protection regime has to be implemented (under which all renewable energies will be pushed) and suitable regulative framework conditions will be implemented. The development from 2025 is following a speed almost as fast as seen in the wind energy since 1995.

The **optimistic-realistic scenario** illustrates the progressive targets first will be met in the period after 2025 as not all of the instruments discussed above are strong enough to stimulate the market development especially within the next 15 years. Although the subsidies of fossil and nuclear electricity production may not be withdrawn and the internalisation of cost of CO_2 reduction will not advance as necessary as assumed for the very optimistic case the other instruments will first be strong enough to reach the *building up phase* in the last period up to 2050. Especially the feed-in-laws and the power purchase agreements supplemented by increasing fossil and nuclear fuel prices can enable an increasing build up of wave and tidal production capacity for the electricity market but real large farms will not be realised before the end of the period. This scenario is adopted form the EREC/Greenpeace (the 2^oC scenario) [28] with respect to installed GW. The electricity produced is somewhat higher as other load factors (full last hours) are used as illustrated in Table 7.4. The EREC study only used a load factor equivalent to 2,500 hours.

For the **pessimistic scenario** it is assumed that drivers will make the wave and tidal development ongoing at a low level beyond 2025 but they will be too weak to enable a high and continuing diffusion as expected for the *optimistic-realistic* or even the *very optimistic* scenario. Wave and tidal energy power plants will only develop slowly up to 2050 not taking full use of mass production advantage. The effort as described above will neither be sufficient to push a strong first development phase nor the second phase of participating in the electricity market. It is assumed that the application of wave and tidal power plants will only have a slight increase all over the world.

Figure 7.3 illustrates the scenario development while Table 7.3 gives details on the installed capacity. Each of the scenarios starts in the year 2007 with an installed capacity of 1GW.

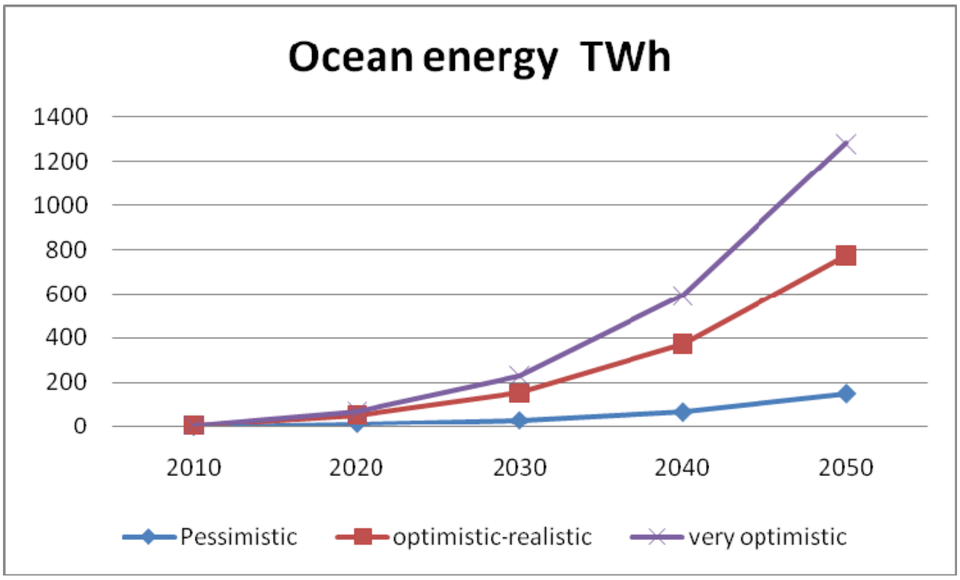

Figure 7.3: NEEDS market development scenarios for wave and tidal power plants

Table 7.3: Installed capacity within the different market development scenarios

GW	2007	2010	2020	2025	2030	2040	2050
Very optimistic	0.4	1	20.4	40	61	149	309
Optimistic-realistic	0.4	1	17	30	44	98	194
Pessimistic	0.4	0.4	4.8	7.4	10	20	40

Table 7.4 compares the wave and tidal electricity production with the worlds electricity demand as provided by scenarios by EREC/Greenpeace (the 2^{o}C scenario) [28].

As can be seen the load hours are increased different in the three scenarios as it strongly depends of the amount of devices deployed. This part of the learning effect is not included in the effect on manufacturing cost using the learning curve, see more next section.

Table 7.4: Wave and tidal generated electricity and its comparison with the world wide electricity demand as proposed in scenarios by Greenpeace and EREC [28]

Wave and tidal electricity		**2007**	**2010**	**2020**	**2025**	**2030**	**2040**	**2050**
World electricity demand (EREC)	TWh	17,031	17,031	19,315	22,507	23,690	24,872	27,524
Wave and tidal energy								
Full load hours	h	3,000	3,000	3,450	3,623	3,795	3,985	4,144
Very optimistic	TWh	1	3	70	151	231	593	1.281
	%	0.0	0.0	0.3	0.6	1.0	2.2	4.2
Full load hours	h	3,000	3,000	3,000	3,225	3,450	3,795	3,985
Optimistic-realistic	TWh	1	3	51	101	152	372	773
	%	0.0	0.0	0.2	0.4	0.6	1.4	2.5
Full load hours	h	3,000	3,000	3,000	3,000	3,000	3,450	3,795
Pessimistic	TWh	1	1	14	22	30	69	152
	%	0.0	0.0	0.1	0.1	0.1	0.3	0.5

7.4 Main competitors of wave and tidal plants and benchmark technologies

In this chapter wave and tidal power plants are compared with the other reference technologies from the NEEDS study. The market segment in which the competition takes place is dispatchable base and mid-load electricity supply. Only the development targets of the main technologies in 2050 are set into relation.

In 2050 near-to-zero emission technologies will be the benchmark. Geothermal power plants, hydro power plants and, mainly in the base load sector, biomass and solar plants will altogether be advantageous compared with wave and tidal power plants in Europe. They are expected to deliver relatively cheap dispatchable electricity for the base and mid-load market.

They do not show significant disadvantages: Only the higher space intensity and particle emission of biomass for energy use and the high water demand of hydro power plants are negative aspects in the balance. Concerning hydropower only large storage plants are considered here, as only they can deliver dispatchable bulk energy in base and mid-load sector. But, hydro power plants and wave and tidal power plants do not compete in the same regions. Solar thermal power plants and onshore wind power plants have the disadvantage of relatively high space/land use demand. This argument is crucial due to the high demand for land in Europe. The group of geothermal, hydro, solar, wind and biomass plants is a benchmark for wave and tidal technologies insofar as this group is expected to define the lowest cost level of electricity generation in 2050.

Coal and natural gas power plants are expected to have higher costs of electricity in 2050 than wave and tidal plants. One reason lays in the expected general trend of rising fossil fuel prices. On the other hand costs for carbon capturing and storage are expected to impose a relevant adder to fossil fuel prices. As another aspect, falling back on substantial import of coal and gas would damage the European energy autonomy. Coal and gas fired power plants have the advantage of a little space demand of the plant itself; the mining of the fossil fuels meanwhile has a space demand to be considered. They are benchmark technologies for wave and tidal inasmuch they define the cost level under which wave and tidal technologies should definitely stay to play any significant role in the electricity supply in 2050.

For nuclear power stations the development of costs is uncertain. An important issue for the deployment of nuclear power will be the public acceptance. The relevance of nuclear energy facilities in armed conflicts and instable regions is rather a social than a technical problem, too. It will have to be discussed even more extensively with a rising deployment of fast breeder reactors. A further unsolved problem is the need of final storage of the very long-lasting nuclear wastes. Even if advanced technologies will minimize nuclear wastes during operation, the core of deconstructed nuclear power plants will presumably have to be stored safely for very long periods. Nuclear power plants have the advantage of a little space demand at the location of the plant. But again space is exhausted by the uranium mining.

An alternative to wave and tidal power plants in Europe is the import of solar thermal power from high insulation areas in North Africa and Middle East. The lower costs of electricity in the MENA region compensate or even over-compensate the transmission costs to Europe. Solar thermal import has the advantage of much less land demand in Europe. On the other hand a large share of electricity import means reduced energy autonomy in Europe and bears risks to the security of supply. The fraction of solar import will depend on the energy autonomy policy in 2050 and the stability of the MENA region. It is limited by the intercontinental transmission capacities to be erected up to 2050. Further on the economic development and thus the domestic electricity demand of the MENA countries will determine the fraction of STP electricity to be exported to Europe.

The other power technologies are not addressing the considered market of base or mid-load dispatchable energy. Photovoltaic power is not dispatchable unless efficient and cheap large-scale electricity storage systems integrated on location will be available. The same holds for wind energy.

Combination of wave, tidal and wind energy has been subjected to several studies [16], [35], [36], [37] showing that a right combination can result in fully dispatchable energy over the year.

8 Future cost

Independent of the three scenarios all of the considered technologies can be expected to develop in the period. The scenarios only determine the overall cost reduction potential within wave energy.

In the following cost figures caused by the deployment scenarios up to 2050 have been based on the methods described in the two NEEDS reports:

- Technology foresight method, [41]
- Analysis based on experience curve [42]

As mentioned earlier only data from one developers has been made available for the NEEDS project. The figures in the following are therefore based on input from this developer: Wave Dragon. It is the auditors assessment that these figures can be taken as representative for high bulk production of electricity. The cost will probably be too low when looking of power production at low scale.

In comparison with most of the other technologies no significant change in the technology have been anticipated in the period caused by the fact that when first the technology has been fit for the sea state (wave period, length and height) there is only minor improvement to be expected. The improvement to be expected is quantified as an increase in the load factor (full last hours) as illustrated in Table 8.1.

Table 8-1 Wave energy load factor development for the very optimistic scenario

Wave and tidal electricity		2007	2010	2020	2025	2030	2040	2050
Load factor	%	0.34	0.34	0.39	0.41	0.43	0.45	0.47
Full load hours	h	3,000	3,000	3,450	3,623	3,795	3,985	4,144

During the period up to 2050 the efficiency can be expected to be improved by developing better control and operational methods as illustrated in the Figure 8.1.

Similar new development of more suitable material and development of new device concepts can change the competiveness but not drastically.

The different scenarios are therefore preliminary expressing how far down the learning curve the technology has progressed and which incentives there can be count on.

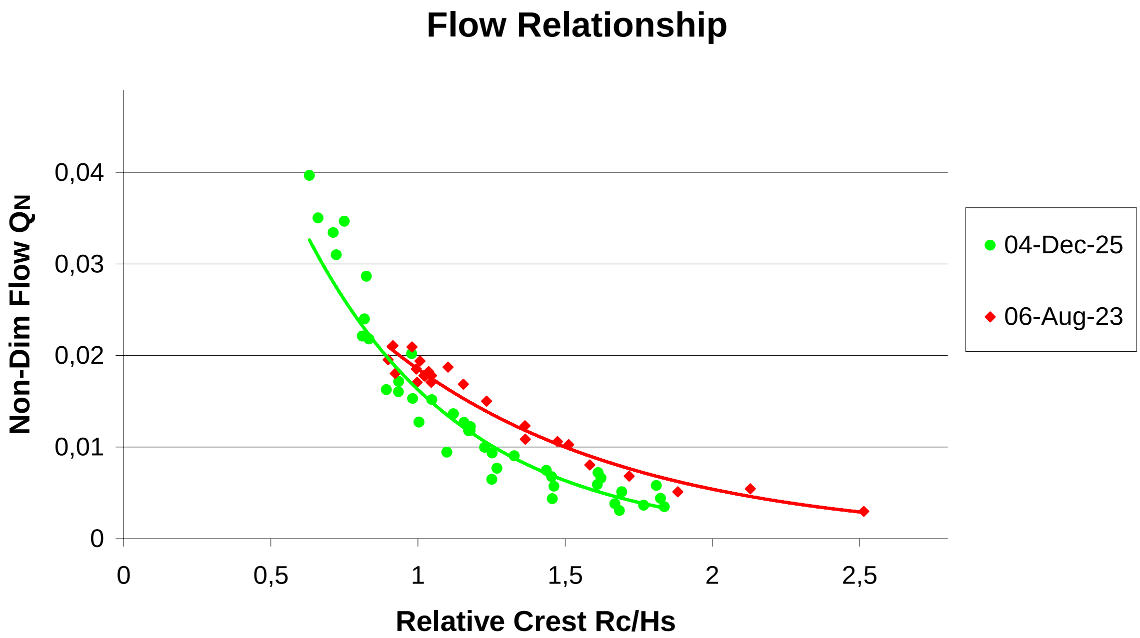

Fig 8.1 Higher power production by learning only by using better codes for controlling [39].

8.1 Development of costs

The present chapter illustrates the calculation of the future investment costs and electricity generation costs by application of the learning rates. Even though different learning curves can be expected for control system and power electronics compared to the main structure of the device and the hydro turbines, on learning rate is assumed for the wave device as the main part of the costs are associated with the main structure of the device and the turbines.

In the calculation we have not included the possibilities of combining wave energy with other uses of the device like:

- Base for growing sea based biomass
- Base for fish farming
- Base for floating wind turbine
- Hydrogen production
- Desalination.

All these activities can decrease the basic cost of the technology but will off course also create additional investment and operation and service.

To utilize the full potentials of sites in Europe where wave and tidal is competitive, the development targets for 2050 must take full advantage of the large variety of technological innovations. Constructions, material science, grid connection will have to be optimised. Thus power plant of wave and tidal power technologies of some 50 to 500MW will be typical in 2050. The optimisation of supply chains and industrial production of wave and tidal power plants will have been enforced, leading to a substantial cost reduction.

All in all, in the next 40 years the main part of the cost reduction potential and efficiency increase should be realized by R&D, learning effects and volume effects. This will presumably lead to costs of electricity of around 0.03-0.04 €/kWh.

The size of the wave farm and the distance to shore is another key element in the cost assumption. We have not distinct between the different scenarios here as there still is plenty of space for deployment of wave devices close to the coast with.

The following basic cost is used:

Reference unit: 7MW unit

Wave farm: 200MW. Same assumption as used by offshore wind [34].

Distance to shore: 10 km

Capacity factor: As illustrated in Table 8.1 and 7.4.

Distribution of power over the year: Not taken into account: usually 2 to 3 times higher energy during winter, but strongly dependant of site.

Specific investment cost year 2007: 3,500 €/kW down to 2,500 €/kW dependant of scenario, as the expectations for mass production will change the base.

Operational and maintenance cost: 0.01 – 0.015 €/kWh. The maintenance and operational cost for the wave device is based on the experience from offshore wind [33] and [34]. The systems to be maintained are of the same kind (hydraulics and power electronics).

Depreciation: 50 years for turbine and basic platform; 20 years for control system, hydraulic and generators/switch gear/ transformer. As mean value are used 25 years.

Learning rate / progress ratio: 14% / 0.86 for the whole period which is at the same level as known form the wind industry. The same level is expected from large civil engineering constructions.

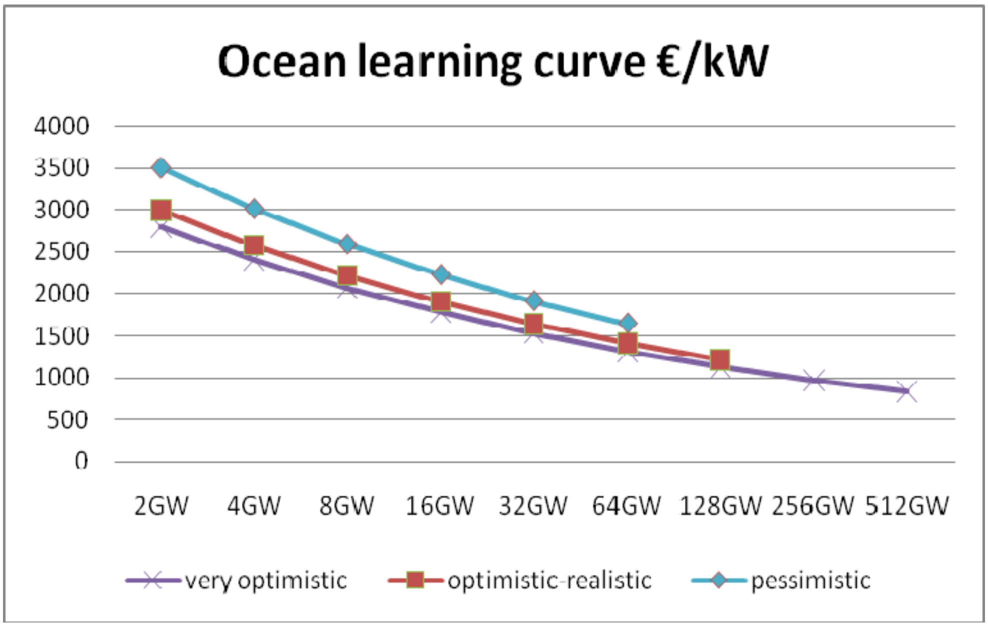

Fig 8.2 Installation cost depending of production accumulated sales volume in GW; progression rate 0.86.

Applying the progress ratio and basic assumption mentioned above the future wave energy investments can be calculated as illustrated in Figure 8.2. As can be expected the investment cost will decrease with increasing accumulated sales depending of the scenarios.

The investment cost is summarised in Table 8.2 and the production price in Table 8.3

Table 8-2 Ocean wave energy electricity investment costs for 2007, 2025 and 2050

Year		**2007**	**2025**	**2050**
Specific investment costs				
Very optimistic	€/kW	2,800	1,200	1,000
Optimistic-realistic	€/kW	3,000	1,500	1,200
Pessimistic	€/kW	3,500	2,000	1,600

Table 8-3 Ocean wave energy electricity production price for 2007, 2025 and 2050

Year		**2007**	**2025**	**2050**
Production cost				
Very optimistic	€/kWh	0.11	0.05	0.03
Optimistic-realistic	€/kWh	0.18	0.06	0.04
Pessimistic	€/kWh	0.22	0.08	0.06

8.2 Sensitivity analysis

The key variable to be analysed could be:

- Progress ratio
- Power produced
- Base line data for production
- Development speed

In Figure 8.3 the influence on the specific investment cost of different progressing ratio is shown.

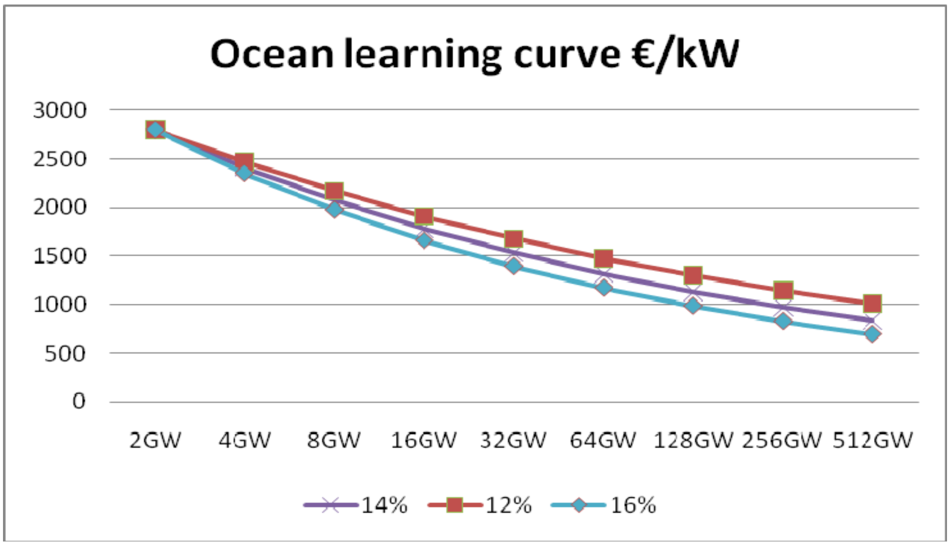

Fig 8.3 Installation cost depending of production accumulated sales volume in GW for the very optimistic study; progression rate 0.84, 0.86 and 0.88.

The influence from shift in baseline assumption, can be judged by looking at the different scenarios in the previous chapter, table 8.2 as such a change directly can be seen in the production price.

A change in development speed can best be judged by comparing the very optimistic scenario with the optimistic-realistic scenario where the difference preliminary is caused by different speed in the development.

Finally can the change in production (GWh/year) be judged directly as the reduction in production directly influences the production price.

8.3 How likely are these technology developments?

Quantitative background scenarios

Development of costs

The cost development projection for wave and tidal energy by 2050 of 0.03-0.04 €/kWh for electricity is alone derived from statements from the developers.

The Carbon Trust Marine Energy Challenge [18] and EPRI [19] have carried out investigations covering more developers. The MEC and EPRI studies assumes specific investment costs of 4,000 €/kW in 2008, 2,000 €/kW in 2020 and 1,500 €/kW in 2050 for wave and tidal plants.

The most important determinant is the assumed development of the specific investment costs for new plants. The future value comprises the assumptions about cost reduction due to technical learning, scale-up and volume effects. The reduction in cost over years up to 2050 seems following the same trend as described in the previous chapter.

As can be seen from the assumption in the previous chapter the specific basic investment cost used in this study is lower than the cost used by MEC and EPRI. The reason for using a higher basic investment cost is probably that these studies are covering small as well as large devices with a wide range of rated power. Further on these studies were carried out some years ahead of the present study at a time where the uncertainty related to production cost probably has been higher.

9 LCA of current wave and tidal devices

Only three LCA studies have until today been conducted:

- Wave Dragon 7MW wave overtopping device [21]
- Pelamis 0.75MW pitching device, Pelamis [43]
- Seagen 1.2MW tidal current device [44]

Detailed information is not available for more than one of the studies [11] as the device developers still are very limited in release of detailed information about their devices.

The general conclusions from the 3 studies are summarised in Table 9.1

Table 9-1: Key data from three different LCA studies on wave and tidal devices

	Wave Dragon	Pelamis	Seagen
Energy pay back	29 month	20 months	14 months
Weight incl. ballast	33,000 tonne	859 tonne	465 tonne
Life time, years	50	25	20

It can be seen that taking the design life time into consideration there is not a big difference between the three devices.

In the following the Wave Dragon device has been used as exponent for the different wave and tidal devices. Even though there today is a large difference in the material used (steel and concrete) for the 3 different devices it is already now known that a change from stele to concrete is considered by e.g. Pelamis [43]. We therefore assume that the Wave Dragon technology can be used as a representative device.

9.1 Description of the technology

The modelling of the electricity production from the current offshore ocean energy technology includes the power producing devices (e.g. Wave Dragon), the internal cables, transformer station, marine transmission cable and a cable transmission station. Each of these steps includes materials, manufacturing, transport, erection, operation and disposal.

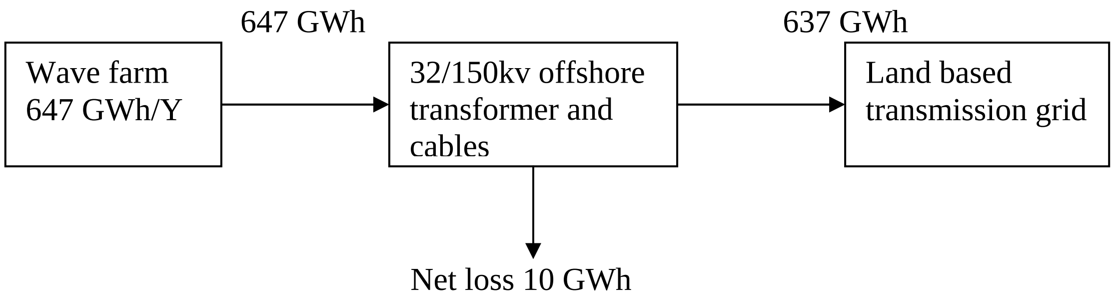

Figure 9.1: LCA system model of the ocean energy farm

Figure 9.1 shows the elements included in the LCA model for the investigated ocean energy technology. This model and associated grid data are the same as used in the NEEDS project for offshore wind farms (WP 10, Horns Rev) [34].

The power output of the investigated wave energy farm will be about the same as for the off-shore wind technology and the distance from the shore will likely be the same, though there will be differences dependent on the ocean energy technology and site selection in question.

The functional unit is 1 kWh, as for all technologies within the NEEDS project delivering electricity to the grid.

The electric power generation from ocean energy farm is thus assumed to be 647GWh/year. The electricity produced from the farm is transmitted via an offshore transformer station and a submarine cable to the transmission grid on land. However, there is a grid loss (net loss) in the transformer and the cables estimated to 10GWh/year for the total plant/farm, and this net loss is also taken into consideration in the electricity modelling.

According to the requirements of Research Stream (RS) 2a, the LCA structure of each technology should consider the fuel supply, operation, production and disposal. But in the case of ocean energy technology, the fuel supply is not relevant, thus only the other three phases: production, operation and disposal are considered.

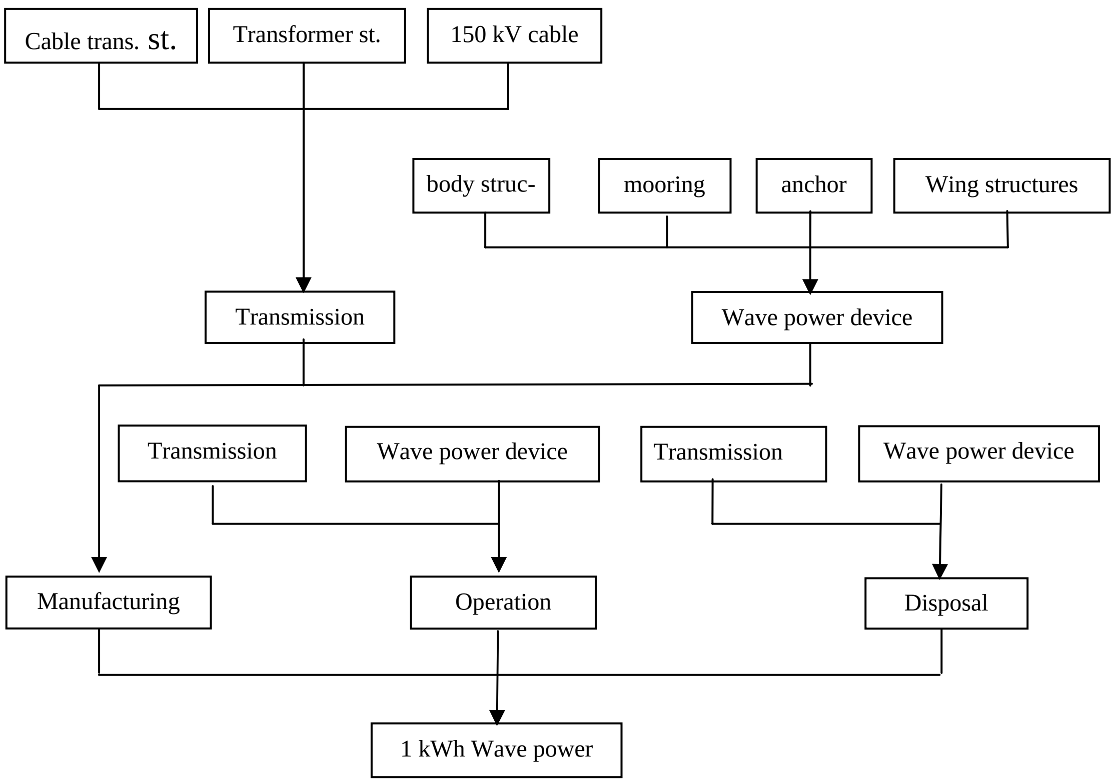

Figure 9.1: LCA model for Wave energy farm, case Wave Dragon [11]

The figure illustrates the structure of the LCA model for Wave Dragon, which represents ocean energy. The technology itself is described in chapter 4.6.6.
A summary of the relevant data for Wave Dragon is shown in *Table 9-2*.

Disposal: This includes dismantling and transport to the final disposal site (recycling, incineration or deposit). At recycling, it is limited to the point where the material is ready for reuse.

Production: Production includes the manufacturing of bodies, turbines, generators mooring systems etc. as well as the manufacturing of the transmission grid. Transportation of the components to the site is also included.

Operation: Change of oil, anodes, lubrication etc. and transport to and from the ocean energy devices are included in the operation stage. Furthermore, maintenance of the ocean energy devices is also included. The onshore transport is by truck, while vessels are used at sea.

Table 9-2: Overview of the relevant data for the current ocean energy technology

Parameter	**Present/2008**		**Unit**
	Turbine	**Plant/Farm**	
Size	7	23 x 7 = 160	MW
Water depth	50 - 100	50 - 100	m
Foundation type:	6 – 8 concrete buckets		
Electrical efficiency	90		%
Life time for turbines	40 – 80	40 – 80	years
Life time for transmission		40	years
Electricity production	8.088E+06	6.47E+08	kWh/year
Full load hours	4,044		h/year
Main data sources	LCA for Wave Dragon [11]		

9.2 Material flow data and sources

Current ocean energy technology

The current ocean energy technology model is mainly based on data from LCA for wave energy [11]. In this project the material flows were based on data from the inventor and communication with associated advisors, potential suppliers and generic data from comparable products and processes. See Annex 1 for examples.

The material flows and processes in [11] were modelled with Gabi IV [45], which is a rather different tool than the current application of Ecospold used in the NEEDS project, concerning both the available processes and the methodology. A major difference in this case is that Ecospold does not credit materials and the embedded energy when recycled after decommissioning.

In the case of wave energy, concrete is the all-dominating material but the available materials, or *processes*, in the Ecospold database; *concrete, exacting, with de-icing salt contact, at plant* and *concrete, normal, at plant* (in a Swiss context) are not necessarily adequate when it comes to represent the right mix of constituents, transport etc. The deviation is not larger than it can be accepted compared to the general accuracy of the input data.

9.3 Results

9.3.1 Key emissions and land use

The data are for one kilowatt-hour of electricity delivered to the grid. The complete emissions related to the current ocean energy technology are shown in Annex 1.

Table 9-3: Key emissions and land use for the reference technology (current technology).

Parameter	Path	Present, kWh_a	Unit
Carbon dioxide, fossil	air	1,32E-02	kg
Methane, fossil	air	2,96E-05	kg
Nitrogen oxides	air	4,89E-05	kg
NMVOC	air	1,04E-05	kg
Sulphur dioxide	air	6,39E-05	kg
PM 2,5	air	1,45E-05	kg
PM10	air	3,57E-05	kg
Occupation, agricultural and fore-stall area	resource	4,87E-04	m^2a
Occupation, built up area incl. mineral extraction and dump sites	resource	6,38E-04	m^2a

9.3.2 Contribution analysis for the main life cycle phases

The present assessment shows that the environmental impacts of the current ocean energy farm is concentrated mainly in the manufacturing stage and to a lesser extend in the operational phase, and with a minimum in the disposal stage 9-4. The use of steel bars and cement in the production stage is by far the main contributor to the environmental impact. Therefore it is very important to choose the right materials in the design phase and to some extend consider their re-usability at the end of the lifecycle.

Table 9-5: Key emissions and land use of the main life cycle phases for the current ocean energy technology

Parameter	Path	Current offshore wind farm				Unit
		Total	Manufacturing	Operation	Disposal	
Carbon dioxide, fossil	air	1,32E-02	1,25E-02	5,12E-04	2,03E-04	kg
Methane, fossil	air	2,96E-05	2,90E-05	3,67E-07	1,67E-07	kg
Nitrogen oxides	air	4,89E-05	4,16E-05	6,28E-06	9,95E-07	kg
NMVOC	air	1,04E-05	8,94E-06	1,07E-06	3,45E-07	kg
Sulphur dioxide	air	6,39E-05	6,29E-05	7,85E-07	2,58E-07	kg
PM2,5	air	1,45E-05	1,37E-05	5,74E-07	1,68E-07	kg
PM10	air	3,57E-05	3,45E-05	6,29E-07	5,42E-07	kg
Occupation, agricultural and forestall area	resource	4,87E-04	4,85E-04	1,58E-06	9,94E-07	m^2a
Occupation, built up area incl. mineral extraction and dump sites	resource	6,38E-04	6,33E-04	1,70E-06	3,24E-06	m^2a

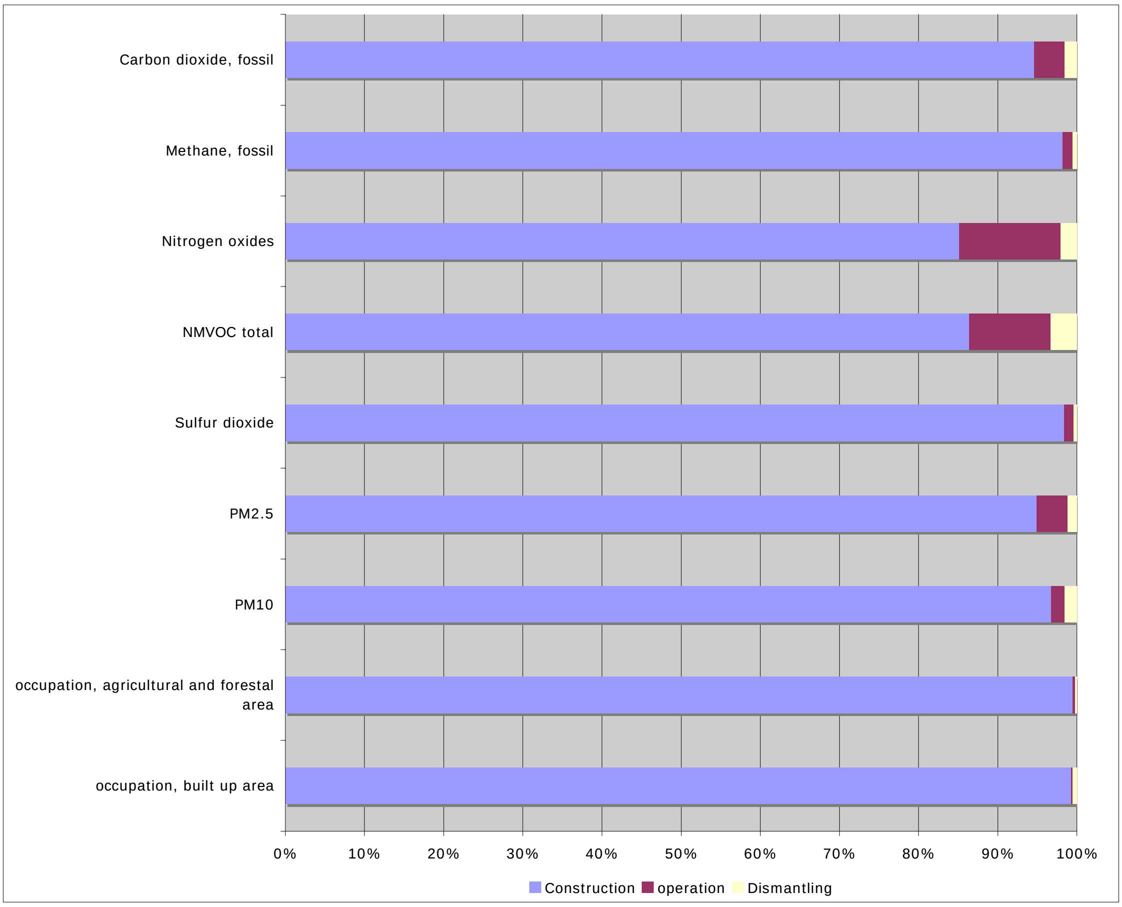

Figure 9-2: Contribution analysis of the key emissions for the main life cycle phases.

The figure shows the impact from the present/2025 PE technology. It is obvious that ocean energy, like most renewable energy sources, has its main impact in the construction phase.

9.4 LCA of future ocean energy technology

Ocean energy technology has no commercial track record yet so the future is uncertain in respect of which concept(s) will be prevailing, which changes can and will be made in choice of materials and how much of this material can be saved with the advancement of the technology.

9.4.1 Description of the technology

The electricity modelling of the future ocean energy technology is the same as for the present technology and includes the energy transforming units, the internal cables, the transformer station, the marine transmission cable and a cable transmission station. Each of these includes materials, manufacturing, transport, erection, operation and disposal. The output of the future ocean energy technology is electricity delivered to the grid and the functional unit is 1 kWh. For the future technology the partners in the NEEDS project decided that each technology should be presented in three scenarios for 2025 and 2050:

- Very optimistic development
- Optimistic-realistic development
- Pessimistic development

There has been made a lot of calculations end estimates on different technologies and for Wave Dragon these calculations has in this case of for practical reasons been expressed as three different span of lifetime; 40, 60 and 80 years. Using the different lifetime is giving the same results as reducing the material in the same proportion.

The input of materials for Wave Dragon will be the same for the scenarios:

- *present* and *pessimistic 2025* (40 years lifespan)
- *2025 realistic optimistic*, *2025 very optimistic* and *2050 pessimistic (60* years lifespan)
- *2050 realistic optimistic* and *2050 very optimistic (80* years lifespan)

The parts *mooring system*, *generator* and *transformer* are replaced one time within the whole lifespan, while all other parts are expected to endure the whole lifespan.

Though only three different configurations have been investigated there is six different outputs due to differences in the impacts of the materials used as input, as can be seen in the choice of material.

Table 9-6: Key emissions and land use for future ocean energy technologies

Parameter	Path	Unit	2025 Pessimistic	2025 Optimistic realistic	2025 Very optimistic	2050 Pessimistic	2050 Realistic optimistic	2050 Very optimistic
Carbon dioxide, fossil	air	kg	1,32E-02	7,83E-03	7,36E-03	7,88E-03	7,67E-03	4,92E-03
Methane, fossil	air	kg	2,96E-05	1,64E-05	1,49E-05	1,74E-05	1,40E-05	9,35E-06
Nitrogen oxides	air	kg	4,89E-05	2,71E-05	2,64E-05	3,33E-05	2,60E-05	1,98E-05
NMVOC total	air	kg	1,04E-05	6,13E-06	5,98E-06	6,23E-06	6,19E-06	4,45E-06
Sulfur dioxide	air	kg	6,39E-05	2,19E-05	2,03E-05	2,78E-05	1,78E-05	1,09E-05
PM 2.5	air	kg	1,45E-05	6,99E-06	6,61E-06	7,75E-06	6,34E-06	4,93E-06
PM 10	air	kg	2,12E-05	1,12E-05	1,10E-05	1,15E-05	1,02E-05	8,12E-06
Occupation, agricultural and forestall area	Resource	m2a	4,87E-04	2,65E-04	2,66E-04	2,68E-04	2,45E-04	1,95E-04
Occupation, built up area incl. mineral extraction and dump sites	Resource	m2a	6,38E-04	3,13E-04	3,12E-04	3,24E-04	3,16E-04	2,31E-04

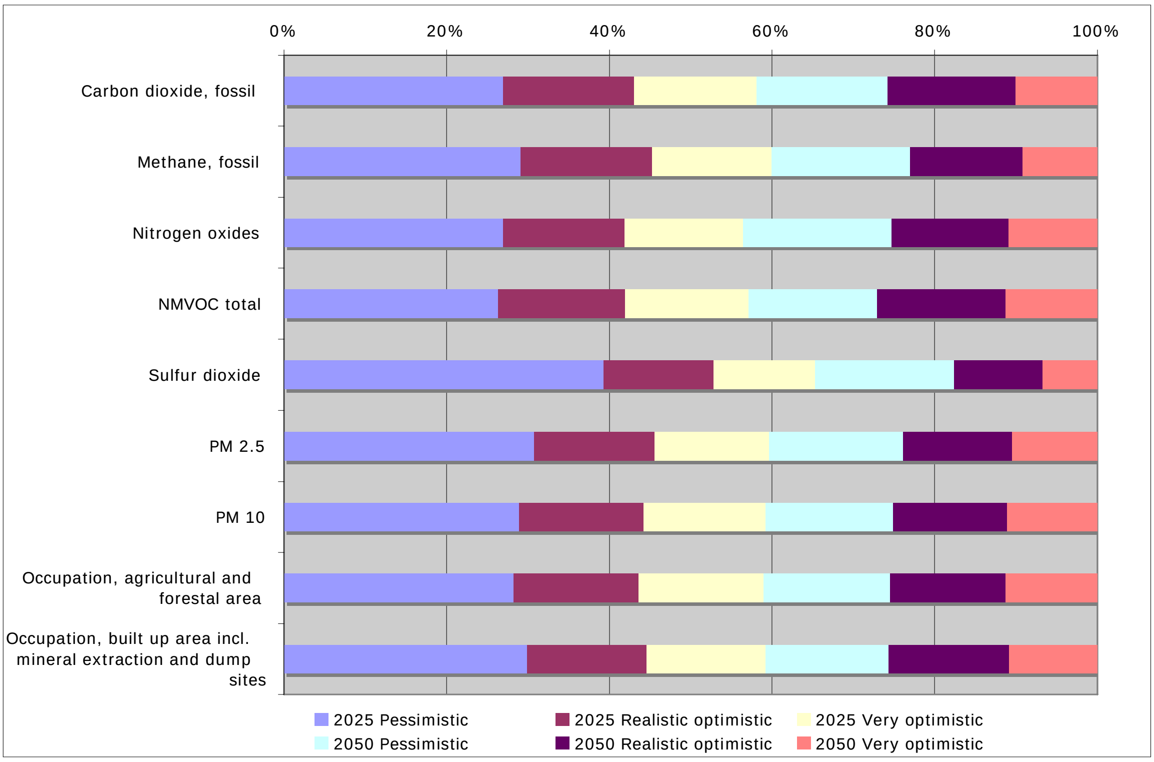

Figure 9-3: Contribution analysis for the different 2025 and 2050 scenarios.

10 Open issues

The following paragraphs summarise the identified open issues regarding the estimation of LCA and cost data for wave and tidal technologies and the proposed solutions.

10.1 Possible localisation of wave and tidal electricity production far off-shore

Issue

In European energy models only plants realised in Europe are included so far. Especially in case of wave and tidal power plants considered within NEEDS there is the necessity to include them into the models also.

By 2050 the electricity generated will be transmitted as high voltage direct current (HVDC) to the bulk request in Central Europe. Therefore, in a few decades the far offshore Atlantic could become production regions of cheap wave and tidal electricity to Europe. This possibility that is also promoted by the CDM tools of the Kyoto protocol could influence somehow the energy systems in Europe. This influence is not considered in the models.

Proposal

We propose to make some estimations of the price of the wave and tidal electricity that could be imported from far off shore and add the possibility of such electricity import in the models as it is done for oil or gas for example.

10.2 Potential externalities that might not be well addressed in the current ExternE methodology

Issue

The potential externalities not covered by ExternE in the field of wave and tidal technologies are mainly:

- Sea use: Sea use, will be another important aspect of wave and tidal power plants. Potential externalities depend on the category of sea which is used and on the question whether the quality of land will be upgraded or degraded during its use.
- Impacts on the sea landscape: Areas covered by wave and tidal can impose an impact on seascape, especially if large or many power plants are constructed in the same area and near shore.

Proposal

As far as we know, no monetary value for these impacts is going to be provided by RS1b, therefore their contribution to the total external costs is not going to be quantified. However, at least estimation in physical terms per unit of electricity should be produced.

10.3 Life cycle assessment in general

Issue

Regarding existing and forthcoming LCA studies of solar wave and tidal plants some general problems arise carrying out the LCA:

- At the moment, it is not clear which of the parts of a wave and tidal plant will be produced in Europe and which in the less industrially developed countries. This would become relevant for the LCA because of different conditions of production in the different countries. On the other hand, there are no LCA known regarding the production of materials like steel, aluminium, concrete, and of electricity in those countries in which the solar thermal power plants will be build.
- The end-of-use phase of the wave and tidal power plants is not considered so far in any concept for these technologies.

Proposal

In a first estimation the LCA will be carried out using data modules representing European conditions. In a sensitivity analysis altering conditions for the production in development countries and for the end-of-use phase could be performed and potential errors within the LCA could be estimated.

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12 Annex 1

The inventory for Wave Dragon is based on different methodology, as described on chapter 9. Below are two examples on how the amount of materials listed in the inventory is determined.

Table 12-1: Inventory for generators for Wave Dragon (Ecospold)

		IndexNumber				28507			
		3702	3703	3508	3706	3707	3708	3709	3792
Index		Name	Location	Infrastructure-Process	Unit	generators, wave energy, 7MW	UncertaintyType	StandardDeviation95%	GeneralComment
		Location				RER			
		Infrastructure-Process				1			
		Unit				unit			
28507	products	generators, wave energy, 7MW	RER	1	unit	1			
4131	technosphere	ferronickel, 25% Ni, at plant	GLO	0	kg	1,50E+3	1	0,00	(,,,,,); approximation for magnets
992		copper, at regional storage	RER	0	kg	5,80E+3	1	3,00	(,,,,,);
961		cast iron, at plant	RER	0	kg	1,09E+4	1	1,05	(,,,,,);
1130		steel, electric, un- and low-alloyed, at plant	RER	0	kg	1,00E+4	1	1,05	(,,,,,);
1265		polypropylene, granulate, at plant	RER	0	kg	2,00E+1	1	1,05	(,,,,,); for plastics (insulation)
36		glass fibre, at plant	RER	0	kg	2,80E+2	1	0,00	(,,,,,);
1845		transport, lorry 28t	CH	0	tkm	1,43E+3	1	2,06	(2,4,1,1,1,5); the metals have to be transported to the factory first (assuming 300km)
1841		transport, freight, rail	RER	0	tkm	4,28E+4	1	2,06	(2,4,1,1,1,5); Unknown origin. A distance of 1500 km is assumed. Rail is chosen as a mix between all realistic means of transportation.

The quantity of materials required for the permanent magnet generators is determined by the use of software (Belt Electric), which is able to calculate both the need for active and passive materials. The calculation is based on the capacity of each generator and the rotational speed (RPM)

Since permanent magnet generators are a rather new technology it is possible that the future will bring stronger magnets and generators with less need for materials.

Table 12-2: Inventory for the electrical transformers for Wave Dragon (Ecospold)

		IndexNumber				28506			
		3702	3703	3508	3706	3707	3708	3709	3792
Index		Name	Location	InfrastructureProcess	Unit	transformers, wave energy, 7MW	UncertaintyType	StandardDeviation95%	GeneralComment
		Location				RER			
		InfrastructureProcess				1			
		Unit				unit			
28506	products	transformers, wave energy, 7MW	RER	1	unit	1			
992	technosphere	copper, at regional storage	RER	0	kg	3,50E+3	1	3,00	(,,,,,);
4805		aluminium, production mix, at plant	RER	0	kg	1,00E+2	1	1,05	(,,,,,);
942		reinforcing steel, at plant	RER	0	kg	9,00E+3	1	3,00	(,,,,,); as proxy for Steel
853		synthetic rubber, at plant	RER	0	kg	9,00E+3	1	1,05	(,,,,,);
1265		polypropylene, granulate, at plant	RER	0	kg	4,00E+2	1	1,05	(,,,,,);
3819		silicone product, at plant	RER	0	kg	6,80E+3	1	1,05	(,,,,,); for silicon oil
1130		steel, electric, un- and low-alloyed, at plant	RER	0	kg	7,00E+3	1	1,05	(,,,,,);
1845		transport, lorry 28t	CH	0	tkm	1,79E+3	1	2,06	(2,4,1,1,1,5); the metals etc. have to be transported to the factory first (assuming 300km)
1841		transport, freight, rail	RER	0	tkm	5,37E+4	1	2,06	(2,4,1,1,1,5); Unknown origin. A distance of 1500 km is assumed. Rail is chosen as a mix between all realistic means of transportation.

The quantity of materials required for the four 2 MW transformers is determined by using an inventory for an LCA of a 10 MW ABB transformer, assuming there is a somewhat higher requirement for materials when the capacity is dispersed on more smaller units.

If the configuration changes (fewer units or less capacity margin is required) the need for materials will decline proportionally. This is even more the case if the transformer can last for the full lifetime of the (Wave Dragon) unit, so it won't be necessary to change it as a part of a major overhaul as assumed in this project.