ENERGY TECHNOLOGY ROADMAPS SYNTHESIS: OCEAN ENERGY

1. OVERVIEW

Introduction

Four marine energy technology roadmaps are reviewed here, produced for the UK Department of Trade and Industry (DTI), the World Energy Council (WEC), the International Energy Agency (IEA) and the Carbon Trust (CT). This introduction summarises their main themes. More detail is presented in the individual roadmap templates.

Marine energy R&D has seen significant expansion and progression recently, supported by a series of policy and industry initiatives. For example, the European Marine Energy Centre (EMEC) is hosting a number of wave and tidal flow prototypes, and the most advanced devices are now being deployed in full-scale trials (see the Marine Energy Research Landscape).

The most recent developments are not reflected in roadmaps produced even one or two years ago, and earlier roadmaps may also make assumptions (e.g. on current and projected costs of conventional generation) that differ from more recent studies. At the same time, many of the findings and recommendations of earlier roadmaps remain relevant. Although policies and regulations can change over relatively short timescales, building up technology development capacity takes longer.

Discussion

Scope: technology and geographic focus

The recent growth and diversification in marine energy R&D is reflected in differences of scope and content of the roadmaps. Two of the earlier roadmaps reviewed here (the 2001 DTI / Arup study and the 2001 WEC survey) both omit tidal flow technology (added in the 2004 WEC survey). This suggests that tidal flow has emerged as a significant prospect relatively recently. The wave energy roadmaps suggest growing attention on nearshore and offshore devices, rather than shoreline devices.

Despite its recent expansion, marine energy R&D is undertaken by a relatively small international community of university researchers, developer firms and support agencies, concentrated in a few regions and countries. The UK, with a favourable resource and research base and growing policy interest, has been at the centre of much of the recent activity. Although two of the roadmaps reviewed here are international in scope, all were developed by UK-based consultants or researchers.

Method: how was the roadmap assembled?

Three of the studies (for the DTI, IEA and CT) involved consultation with industry stakeholders, and made a detailed examination of technical and institutional issues facing the sector. By contrast, the WEC (and summary DTI) reports are based on secondary sources and references, and are limited to a more general outlining of opportunities and barriers.

However, of the three more detailed studies, only the CT study makes an assessment of the present and future unit cost of marine energy. The other studies identify the technical, economic and institutional issues that need to be resolved for an accurate cost assessment to be made, such as developing a robust testing and verification procedure for device prototypes.

Findings: strengths and challenges of the research field

All the roadmaps conclude that marine energy has the potential to make a significant contribution to energy supply in the UK and internationally. All also find that the UK is well placed to develop the technology, given its resource and research base, and established industries with potential for technology transfer. At the same time, all recognise that this potential will take time to be developed, and requires a number of interacting economic, technical and institutional barriers to be overcome.

Economically, the broad challenge is to become cost competitive with established generation technologies. While this confronts all emerging technologies, the marine sector lacks large industrial 'prime movers' – R&D in the sector is being driven by small teams, with limited resources to address the challenges they face (although some developer firms have recently established relatively strong industrial consortia).

Technologically, marine energy spans a range of prototype devices at different stages of development, from conceptual designs to full-scale demonstrators. Tidal flow and wave devices face different sets of opportunities and challenges. Tidal flow prototype designs are relatively alike, and the main challenges relate to prototype proving, site selection and local impacts. Wave prototype designs are a more diverse, and a wider range of R&D challenges and support issues are involved.

Despite this diversity, the different roadmaps identify similar sets of technical challenges, in both core components (e.g. moorings, seals and bearings, power cables and hydraulics) and wider issues (such as resource assessment and forecasting, power smoothing and storage, and O&M). As the IEA study notes, however, many of these issues manifest differently for different devices, especially for wave.

Institutionally, key challenges relate to licensing and permitting, environmental impact assessment, and encouraging information exchange. A generic issue, identified by all the roadmaps, is the lack of performance and reliability data for working prototypes in real operating conditions. These issues have been addressed in recent policy measures (see the Research Landscape).

Recommendations: R&D priorities, institutional reforms

All the roadmaps outline generic R&D programmes to address the common technical challenges in components and operations (these are most detailed in the Arup and IEA reports). A wider set of recommendations is also identified, to address issues such as environmental impact assessment, resource assessment and real-time resource forecasting.

A repeated theme is the need for more collaborative R&D, spanning different developers and research groups, and greater international networking. At the same time, the IEA report notes that lack of design consensus (especially in wave energy) means that support is also required for device-specific R&D, and for independent standard testing methods. These issues have been targeted in recent initiatives (e.g. the setting up of the European Marine Energy Centre). Another common these is the opportunities for technology transfer from established engineering sectors and the emerging offshore wind sector. At the same time, the Arup study identifies barriers to transfer, given the different risk/reward profiles of different sectors.

Conclusion

Despite some differences in motivation, scope and method, the different roadmaps agree on the broad opportunities and barriers facing marine energy. They also develop similar sets of recommendations for R&D priorities and institutional reforms. Many of these gaps and barriers have been targeted by recent policy and industry initiatives, and these changes have been associated with a significant increase in innovation activity in the sector. At the same time, many challenges remain, and the longer term impact of these measures is not yet clear.

2. STATUS AND RESEARCH AND DEVELOPMENT PRIORITIES 2003: WAVE & MARINE CURRENT ENERGY

International Energy Agency

This roadmap was produced on behalf of the International Energy Agency (IEA) 'Implementing Agreement' on Ocean Energy, which is designed to promote international co-operation in R&D. The roadmap aims to identify opportunities for the IEA to supplement national R&D programmes, especially in generic research. The study involved consultation with developers, university researchers and industry experts.

The report includes introductory sections on the tidal current and wave resource, conversion technology, prototype and demonstration activity, development status, economics and environmental impacts. For tidal current, 3 generic concepts and 4 prototype devices are reviewed; for wave, over 20 prototype devices are analysed (grouped into shoreline, nearshore and offshore). Each is positioned on a development spectrum, ranging from 'concept only' to 'full-scale prototype'. The report then summarises developments in 18 countries and the EU, in terms of their resource bases, funding arrangements, R,D&D activities and current technology status.

The roadmap reaches a number of conclusions:

- both wave and tidal current have 'huge market potential' internationally.
- tidal current is progressing, with a few designs being tested in real sea conditions; additional support is required to understand the size and limits of the tidal resource, and facilitate deployment at suitable sites.
- wave energy has clear potential, but the development route is much less clear than for tidal. There are many more varied designs of wave devices, at different stages of development. A few promising designs are being developed by strong company consortia, but many promising ideas are not matched with credible developers, and are progressing more slowly.
- the wide variety of prototype designs (especially in wave) presents difficulties for identifying generic R&D needs; many R&D priorities are device-specific.
- a fair, objective and robust method for assessing different concepts is essential.

The report identifies a set of generic development needs, including: resource assessment, market size prediction, technology and information exchange, testing and certification processes and environmental impact assessment. A set of common technical research issues are also identified, including mooring technology, electrical connection, power conditioning, power forecasting, and O&M methods. However, the report notes that many of these generic issues are manifested differently in different devices, so that generic research is of limited value. This implies that public programmes fund specific designs, and not just generic R&D. It also places critical importance on consistent, reliable and robust assessment methodologies, to help funders select the most promising designs.

The report goes on to identify R&D priorities for different types of devices, whether they are generic or device specific, and opportunities for task- or cost-sharing across IEA members (see template for more details).

3. DTI TECHNOLOGY ROADMAP - WAVE ENERGY

UK Department of Trade and Industry

The DTI Wave Energy Technology Route Map is a short report which draws on a more detailed review of wave energy undertaken by consultants Ove Arup (below). The Route Map includes an introduction to the wave energy resource base, conversion technology, market opportunities (both for large/grid-connected and small/off-grid installations), and a short review of design prototypes.

The report's overall conclusions are:

- wave energy is unlikely to make a significant short-term contribution to energy supplies, but it could become an 'important option' after 2010, providing that demanding targets for progress are set.
- barriers to realising this potential are uncertain commercial prospects, long development timescales and the short investment horizons of industry.
- the UK has significant R&D strengths in wave energy and related industries.
- there is no consensus of optimal design, and alternative approaches will continue to run in parallel for the foreseeable future. Shoreline devices are technically developed but commercially unproven; offshore devices are at an earlier R&D stage, with many concepts still needing verification. All types need to demonstrate their long-term performance and reliability
- there are particular opportunities in the shorter term for isolated off-grid installations.

A number of generic R&D challenges are identified:

- developing and applying a systematic method for evaluating devices, both existing designs and new concepts.
- testing and monitoring the performance and reliability of prototypes in real operating conditions.
- there is series of generic technology gaps / research priorities, including: moorings, power cable connections, hydraulic systems, grid connection, power storage and smoothing, modelling system and device performance, real time wave forecasting, seals and bearings, and direct-drive generators.

Three non-technical issues are highlighted:

- the need for a simplified offshore planning/consenting/licensing regime (including offshore wind as well as marine energy).
- impartial research on environmental impacts, and the development of environmental impact assessment (EIA) protocols.
- publishing technical and economic performance data from prototype trials, enabling better understanding of the sector's overall prospects.

A generic technology 'Route Map' is then elaborated – in practice, a series of development milestones with target dates for completion. Different sets of milestones and target dates are identified for established designs and new concepts (see the roadmap template). For the former, the overall aim is to evaluate long-term prototype performance by 2010; for the latter, to take forwards the most promising designs as small prototypes by 2006.

WAVE ENERGY: TECHNOLOGY TRANSFER AND GENERIC R&D RECOMMENDATIONS

Ove Arup

The Arup study accompanies the DTI report (above). It provides a much greater detailing of the research issues associated with wave energy, and the opportunities, in addressing these, for transferring technology and skills from established industries. The study was developed in consultation with wave developers, university researchers and offshore engineering firms.

Arup's major conclusions are:

- the wave industry has developed successful prototypes for shoreline devices, and is in the process of developing nearshore and offshore prototypes.
- as the industry moves offshore, the opportunity exists for technology transfer from existing industries in offshore oil & gas, civil engineering and manufacturing. There are no major technological barriers to prototype development: design, construction, deployment and operational issues can all be addressed by technology transfer.
- at the same time, there are significant differences between oil & gas and marine energy industries in terms of costs, risks and returns. Unlike the oil & gas sector, the wave energy industry must capture economies of scale and design repeatability savings. Technology transfer also requires that planning approval issues are addressed.
- the offshore wind and wave industries have common interests in several areas, including approvals, subsea cabling, mooring systems, operating and maintenance (O&M) strategies and developing grid capacity.
- the wave energy industry is poorly co-ordinated, with developer teams working independently and (given commercial pressures) secretly. Innovation is being led by small university and private sector teams which lack the capacity to address the full range of R&D challenges involved. Inadequate research capacity and lack of collaboration are slowing down development of the technology.
- there is a lack of investor confidence and wider industry support. The technology is seen as being far from commercialisation, offering high risk and long returns on investment. There have been no successful long-term demonstration projects.

The report identifies a number of key technological and institutional issues where generic R&D would be beneficial, including: regulatory environment, HSE, design codes and verification; construction methods, project cost estimation, mooring systems, O&M, materials, hydraulic/pneumatic systems, subsea cables and connectors, control systems and power quality, and grid connection. Arup consider each of these in terms of: technology issues, potential for technology transfer and generic R&D needs (see template).

A series of recommendations are developed for improved industry co-ordination, technology transfer, prototype development and generic R&D. This distinguishes between immediate priorities for prototype development, and longer term power station development. The report concludes that devices closest to the market should be accelerated to deployment, so helping to build-up confidence in the sector.

4. SURVEY OF ENERGY RESOURCES

World Energy Council

The World Energy Council issues a global *Survey of Energy Resources* every three years. The 2001 survey included chapters on wave energy and tidal barrages. The 2004 survey extended this to include tidal current technology. The chapters, written by individual university or consultancy-based experts, offer overviews of the international research fields, rather than a detailed examination of research priorities and milestones.

The 2004 tidal energy chapter included summaries of: the global resource, capture methods, technology principles, prototype designs, future prospects, and a country-by-country review of recent developments. For tidal current devices, it concluded that although the technology will have little impact in the short term, small commercial developments may appear within the decade, particularly remote / island installations; in the longer term, much larger, strategically significant sites could be exploited.

The 2004 wave energy chapter included summaries of: the research field, resource profile, prototype devices, non-technical challenges, technology prospects and a country-by-country review. The non-technical challenges identified included:

- gross under resourcing, given the challenges involved: the technology is being developed by small firms with typical total investment under US$10m.
- the high costs of licensing, permitting and environmental impact assessment, even for small-scale prototypes.
- the need to compete with well-established technologies in liberalised markets.

The 2001 chapter on wave energy identified key socio-political drivers behind a renewed interest in wave energy, a description of the global resource, a technology review, and a country-by-country review. The report highlighted the potential for technology transfer from existing offshore engineering. A timeline R&D roadmap is introduced to illustrate the generic challenges facing the sector. A series of research issues associated with the roadmap are identified, including: moorings and couplings, electrical connectors, cabling, modelling of device arrays, real-time wave forecasting, hydraulics, direct drive generators, and power smoothing and storage.

The report concludes that future costs of offshore wave energy of 5-7p/kWh are possible, depending on: engineering-out device costs as more are built, streamlining planning and regulation procedures, developing economic procedures for grid connection, developing lower cost materials and design and construction methods, accessing long-term contracts and capital grants, and developing standard independent testing and performance assessment methods. More generally, there is a need for a greater support by the financial community, and more collaborative R, D&D across device developers, manufacturers, and service providers to avoid duplication and waste.

5. FUTURE MARINE ENERGY

The Carbon Trust

In order to prioritise their future investment in the energy sector, in 2003 the Carbon Trust carried out an assessment of a number of renewable energy technologies in terms of their cost reduction potential, market size and the competitive position of 'UK plc' (Carbon Trust, 2003, *Building Options for UK Renewable Energy*). The *Building Options* report concluded that, unlike onshore wind – where foreign companies dominate high-value elements of the supply chain – UK firms have the opportunity to create competitive positions in all areas of the marine energy sector, including design, manufacture, installation and operation. If wave or tidal stream power generation became cost competitive at scale, the sector has great potential to create value for the UK, with estimates of market share as high as 90% for the UK market and 20% globally by value.

Following the positive prospects for the marine sector highlighted in Building Options study, the Carbon Trust launched a Marine Energy Challenge (MEC) in 2004. The MEC was a £3.0m, 18-month programme of directed engineering support to accelerate the development of marine renewable energy technologies, and also assess the wider cost- competitiveness and growth potential of wave and tidal stream energy. Eight marine energy devices and concepts were selected to participate in the Challenge, half of which were overseas-based. All of the devices selected were offshore wave energy converters, although detailed studies were also carried out into other technologies, including shoreline and near-shore Oscillating Water Column (OWC) wave energy converters, and tidal stream energy generators.

The *Future Marine Energy* report summarises the findings of the MEC. The report concludes that wave and tidal stream energy have the potential for bulk electricity supply in the UK and worldwide. The potential energy resources are significant, particularly offshore wave energy. The market is likely to be sufficiently large to merit considerable interest in its commercial development. There are no fundamental engineering barriers to the technical proving of devices, but considerable further engineering effort is necessary to see wave energy converters and tidal stream energy generators succeed. Substantial public and private investment for R,D&D is likely to be needed for at least 10 years, and public support for project development will be necessary for at least 15 years.

After the completion of the MEC in 2006, the Carbon Trust launched a follow-on £3.5m funding programme, the Marine Energy Accelerator (MEA). Funding under the MEA is directed onto three key themes emerging from the Marine Energy Challenge: (i) *device technologies*: development of new device concepts with potential for significantly lower costs than current front-runner devices; (ii) *component technologies:* research and development into specific component technologies that are common causes of high costs; (iii) *installation, operation & maintenance*: development of low cost installation, operation and maintenance strategies.

6. SUMMARY TABLE

	IEA Ocean Energy	DTI Wave Energy	WEC Survey	Carbon Trust
Date	2003	2002	2001, 2004	2006
Purpose	To identify potential impact of IEA-funded R&D, especially in generic research.	To identify potential impact of DTI-funded R&D. Part of wider DTI review of its renewable energy support.	Tri-annual overview of research field issued by UN-accredited NGO	Final report on the Carbon Trust's *Marine Energy Challenge*, a 2-year research programme intended to accelerate innovation activity.
Method	Commissioned consultancy report (by Future Energy Solutions). Use of stakeholder interviews and workshop.	Commissioned consultancy report (by Ove Arup). Use of interviews and workshop with developer teams.	Research overviews written by industry / academic experts. Country overviews compiled from secondary sources.	Programme of directed engineering support for 8 developer firms. Additional studies also commissioned.
Scope (technology)	Wave energy and tidal stream. Focus on generic (non device specific) research.	Wave energy. Focus on technology transfer, networking and independent testing.	Wave energy and tidal barrages. Tidal steam also included in 2004 report.	Offshore wave energy, with secondary studies into shoreline wave and tidal stream.
Scope (geographical)	Worldwide	UK	Worldwide	UK focus, although the MEC included a overseas-based developer firms.
Timescales	None specified	Up to 2010	Up to 2020	Up to 2020 for most forecasts.
Trends and Drivers ***Consensus:*** *medium*	None specified	Resource availability; climate change; security of supply; domestic industrial opportunities; off-grid niche opportunities.	Resource availability; climate change.	Security and lack of fuel price volatility of marine energy; potential for the UK to play a leading role in developing marine technologies.
Enablers ***Consensus:*** *medium*	Develop / apply robust assessment methodologies; gain better understanding of environmental impacts; fund individual devices, not just generic R&D.	Need for more R&D experience in device development and evaluation; develop strong engineering capabilities in related industries.	More engagement by financial community; more collaborative R&D to avoid duplication and waste; engineer-out costs in materials, design & construction.	Device & system cost reduction; availability of finance; readiness to manage risks; availability of network capacity; environmental and regulatory factors.
Performance targets ***Consensus:*** *low*	None specified.	• For established designs: evaluate prototype performance by 2010 • For new concepts: take forwards most promising designs by 2006	• Offshore demonstrator by 2004 • Full scale technology development by 2020	Estimated deployment of 1.0-2.5GW of each of wave energy and tidal stream energy by 2020, for a total capital cost of £1-2,500 m for each.
Prioritisation of actions?	No	Yes. Distinction between immediate priorities for prototype development, and longer term for power stations.	Yes	YES. Research priorities are identified for wave and tidal in supporting Black & Veatch report.
Sequencing / dependencies	No	No	Yes (3 phases of sequential R&D projects identified to 2020)	No.

Research needs ***Consensus:*** *high*	Priorities are identified by device type. Include: moorings, seals, biofouling, cabling, hydraulics, power conditioning, power forecasting, installation, O&M, design standards, device-resource interaction, cavitation, array effects.	Include: moorings, power cables, hydraulic systems, grid connection, power storage & smoothing, modelling system & device performance, real time wave forecasting, seals & bearings, direct-drive generators.	Include: moorings and couplings, electrical connectors, cabling, modelling of device arrays, real-time wave forecasting, hydraulics, direct drive generators, and power smoothing and storage.	*Tidal*: gearbox, rotors; structural materials; cabling; device-mounted electrical plant; offshore substation; mooring. *Wave*: structural materials, generator, mooring & connection; power converter; cabling; offshore substation
Other actions needed ***Consensus:*** *medium*	Resource assessment and forecasting, market prediction, info. exchange, testing & certification processes, environmental impact assessment (EIA).	Simplified planning, consenting, licensing regime; EIA protocols; technical & economic performance data from prototype trials.	Streamlined planning & regulation procedures, economic procedures for grid connection; independent testing & performance assessment methods; long-term contracts & capital grants.	Consents and permits, resource assessment, bathymetric & geotechnical surveys, ‘proportionate’ environmental impact approach, grid capacity, long term policy framework