Pelamis: experience from concept to connection

BY RICHARD YEMM, DAVID PIZER*, CHRIS RETZLER AND ROSS HENDERSON

Pelamis Wave Power Ltd, 31 Bath Road, Edinburgh, UK

The development of the Pelamis wave energy converter from its conceptual origins to its commercial deployment is reviewed. The early emphasis on designing for survivability and favourable power absorption characteristics focused attention towards a self-referenced articulated line-absorber in an attenuator orientation. A novel joint and control system allow the machine to be actively tuned to provide a resonant response power amplification in small and moderate seas. In severe seas, the machine is left in its default or natural condition, which is benign and non-resonant. Hydraulic rams at the joints provide the primary power take-off with medium-term storage in high-pressure accumulators yielding smooth electricity generation. Land-based modular construction requiring minimal weather windows for rapid offshore installation is an essential engineering feature necessary for viable commercialization. The second-generation Pelamis designs built for E.ON and ScottishPower Renewables are presented, and the scope for further cost reduction and performance enhancements are explained.

Keywords: ocean; wave; power; renewable; energy

1. The Pelamis wave energy converter: fundamental principles

The Pelamis wave energy converter (WEC) is a floating offshore device that converts ocean wave energy into electricity. It is a semi-submerged, articulated structure, composed of multiple cylindrical sections linked by hinged joints. Motion of the hinged joints is restrained by hydraulic rams that pump fluid into high-pressure accumulators, which smooth out the irregular wave by wave-absorbed power. Control of this pumping action allows absorption to be maximized when waves are small and the response to be minimized in storms. Standard variable displacement hydraulic motors then draws a controlled flow from the accumulators to drive induction generators, the displacement of motors is varied in response to the slowly varying system pressure to deliver steady, continuous electrical power output from each joint. All generation systems are housed within the machines, and power is transmitted to the shore using standard sub-sea cables and equipment.

*Author for correspondence (d.pizer@pelamiswave.com).


One contribution of 18 to a Theo Murphy Meeting Issue ‘The peaks and troughs of wave energy: the dreams and the reality’.
To date, four first-generation Pelamis P1 machines (figure 1) and one second-generation P2 machine (for E.ON) have been manufactured and tested. Pelamis Wave Power Ltd (PWP) is currently completing manufacture of a second P2 machine for ScottishPower Renewables. The P2 is the second-generation design of the Pelamis WEC and is the result of over 13 years of development work and operational experience. Extensive optimization work using PWP’s comprehensive suite of proprietary design tools has resulted in a number of major advances in machine configuration and design, which are embodied in the P2 machine.

The P2 has five sections linked by four joints. The sections have a diameter of 4 m and a length of 36 m. The overall machine length is 180 m with an overall weight of approximately 1300 tonnes, the majority of which is sand ballast. It is currently rated at 750 kW and the target capacity factor is 25–40% depending on the conditions at the chosen wave farm site.

The Pelamis WEC concept has a unique combination of power absorption and survivability characteristics, which has been developed into a viable and cost-effective converter through the application of practical engineering design.

(a) Survivability

Survivability considerations were at the core of the development of the Pelamis concept. WECs must cope with a much larger range of input power than any current renewable energy technology. Peak energy levels in stormy conditions are typically 100 times the levels encountered under normal operation. It is, therefore, essential that a WEC concept inherently limits its absorption in rough conditions. Failure to do this would mean that power take-off (PTO) systems and structures have to be rated for much higher levels than is economic, increasing cost and rendering them inefficient at normal operating levels. Pelamis combines the advantages of high-power capture efficiency in small seas with inherent survivability in the harsh marine environment. As wave size increases, the small frontal cross-sectional area and low drag form of the machine allow it to progressively dive under the wave crests, limiting power absorption and thereby loads and motions.

The most extreme loads encountered in the marine environment arise from drag and slamming loads owing to the high water velocities and accelerations experienced in extreme waves. Pelamis is protected against such hydrodynamic loading owing to its sleek, streamlined form. This process is similar to a surfer diving under the wave crests when swimming from the beach, as shown in figure 2.
Pelamis achieves power limiting as wave height increases by smoothly and progressively submerging and emerging locally down the length of the machine, as depicted in figure 3. Once the cross section is locally submerged, the buoyancy force applied by the wave does not grow. The drag and inertia loads continue, but these are inherently kept low owing to the streamlined shape and small local cross section.

Pelamis enjoys another operating and survivability advantage owing to the use of the wave curvature as the source of reaction and power absorption. Waves can only reach a certain steepness before they naturally break and this inherently limits the effective curvature of an individual wave. It is advantageous to use this self-limiting wave curvature rather than elevation as the driving mechanism as this allows Pelamis to make better use of the force and stroke of its PTO rams than an equivalent heaving system, and there is a natural limit of joint angles along the machine. Conversely, a heaving system has to operate efficiently in 1–2 m high seas, but withstand waves of up to 30 m in height. In practice, the heaving system cannot undergo such movements so must be locked down in large seas or have a separate end stop system, both of which will have attendant loads much higher than normal operating conditions.

(b) Power absorption

Most of the energy available over the year is in the form of waves that are small compared with those occurring during storms. It is, therefore, vital that a WEC is able to maximize absorption in such conditions for a given cost of build
and operation. The crudest measure of cost is volume—this sets the basic size of the structural elements and has a direct influence on the average and maximum forces that the system is likely to see. These factors are two of the prime drivers of cost in any engineered system. An effective wave energy absorber must make the most efficient use of volume to absorb the maximum power on average throughout the year.

Pelamis works on the ‘line-absorber’ principle, where waves are absorbed by a long structure extending perpendicular to the approaching wave fronts. This method of absorption allows the highest power capture for a given volume of machine without having to rely on fixed frames of reference with their associated extreme loads and sea-bed construction. This is the most fundamental competitive advantage offered by Pelamis and is analogous to the advantage enjoyed by all modern wind turbines, which use lift to drive the rotor, rather than earlier designs that used drag.

In order to understand the nature and extent of this fundamental advantage, it is necessary to delve into some of the basic physics governing wave power absorption. WECs have theoretical limits on the amount of power they can absorb from a given set of waves, similar to the Betz limit that applies to wind turbines, or the Carnot limit that applies to thermal engines. Understanding the nature and behaviour of these fundamental limits is vital to conceiving and designing an optimal engineering solution. In common with all real systems, there are many factors that reduce the actual output of a WEC from the ultimate performance limits. However, these fundamental limits are well established in scientific literature and represent the ultimate upper limit of performance, thus it is useful to examine the Pelamis limits with respect to other WEC concepts.

An often confusing aspect of wave energy is that a WEC can absorb more energy from the waves around it than is contained within its frontal width facing the seas. This is because the machine is interacting with the entire wave field around it not just with the waves that pass directly under the system. The energy capture of a WEC is often expressed as its ‘capture width’; this is the width of incoming wave that has the same power as that being absorbed by the WEC. Owing to the mathematical relations that govern this aspect of WEC behaviour, the ultimate capture width of a given mode of absorption is a function of the incoming wavelength $\lambda$. For this reason, the ultimate absorption potential of a given configuration of machine is commonly expressed as a fraction of wavelength.

As for the Betz and Carnot limits, these fundamental capture width limits for WECs are based on an idealized system; for WECs, the assumption is infinitesimal waves and responses. However, as proved in many areas, the performance of real physical systems can approach the fundamental limits as their designs become more and more refined. For example, early wind mills typically had a peak performance of less than 10–15% of the Betz limit [1] and an average performance of much less. Through optimal design modern wind turbines can now deliver over 70 per cent of the Betz limit [2] over much of their operating wind speed range. Similarly, Sir Frank Whittle’s first gas turbine achieved an overall efficiency of less than 10 per cent; modern aircraft gas turbines are nearly four times more effective and combined cycle gas power plants can achieve over 50 per cent.

There are several categorizations of the large variety of proposed WEC designs (e.g. [3]). In general, wave energy absorbers can be thought of as wave-makers, with their motion-radiating waves (like a stone cast into a pond that radiates
waves from its impact) that cancel out the incident ocean waves as they pass. This far-field analysis is used to determine the ultimate capture width limit of a given form of WEC.

The most common WEC concept is a heaving body, whereby power is extracted by resisting and controlling the vertical motion of a buoyant body as it bobs up and down. This class of machine is the most common operating principle being actively developed and has become known as a ‘point absorber’. This arrangement creates a monopole radiation pattern as can be seen in figure 4a, creating a circular pattern of waves radiating energy equally in all directions from a device at the centre. Only the components in the direction of the incident waves can interfere in a way that absorbs power. Figure 4b shows waves incident from the left interacting with the radiated waves under optimal response conditions to maximize absorption. The calmed portion of the incident wave pattern to the right of the diagram, down wave from the absorber, indicates absorption. However, it can also be seen that much of the radiated pattern does not result in absorption, but creates a mess of interfering wave fronts. The radiation to the sides and up-wave is wasted energy, which has a detrimental effect on the maximum absorption. Analysis of this case [4] gives a theoretical capture width limit, for a perfectly responding point absorber, of $\lambda/2\pi \approx 0.16\lambda$. It can be seen that, although the capture width may be substantially wider than the machine itself (a general and appealing feature of WECs), most of the point absorber’s response is not able to absorb power owing to its inherent characteristic of radiating in all directions in order to absorb in one direction.

Similar analysis [4] can be made for surging or pitching converters, which have up-wave and down-wave cosine-focused radiation patterns, and give a larger capture width of $\lambda/\pi \approx 0.32\lambda$, as less energy is lost through radiation to the...
Table 1. Capture width limits of different types of wave energy converter.

<table>
<thead>
<tr>
<th>mode of absorption</th>
<th>theoretical capture width</th>
</tr>
</thead>
<tbody>
<tr>
<td>heaving body</td>
<td>$\lambda/2\pi \approx 0.16\lambda$</td>
</tr>
<tr>
<td>surging or pitching</td>
<td>$\lambda/\pi \approx 0.32\lambda$</td>
</tr>
<tr>
<td>heaving-and-surging or heaving-and-pitching</td>
<td>$3\lambda/2\pi \approx 0.48\lambda$</td>
</tr>
<tr>
<td>line absorber length = $\lambda$ [5,6]</td>
<td>$0.50\lambda$</td>
</tr>
<tr>
<td>line absorber length = $2\lambda$ [5]</td>
<td>$0.73\lambda$</td>
</tr>
</tbody>
</table>

side. An appropriate combination of heave and surge can yield a down-wave-focused radiation pattern without the up-wave component and a capture width of $3\lambda/2\pi \approx 0.48\lambda$ is attained, as there is no energy loss through up-wave radiation.

The theoretical line absorber limits, as applies to the Pelamis, are a function of the length of the machine. As depicted in figure 4c, the radiation pattern from a line absorber of length equal to twice the wavelength provides a highly focused radiation pattern with little losses in other directions, and when interfering with the incident wave (figure 4d) provides cancellation (and hence absorption) of the incident wave down wave from the absorber. The theoretical line absorber limit for this case rises to $0.73\lambda$ [5], nearly five times that of a heaving buoy.

These key results are summarized in Table 1.

(c) Engineering embodiment

(i) Self-contained reaction forces

All WECs must act against the force of the waves to absorb the energy. Creating such forces requires something for the PTO mechanism to push against—a source of reaction. Unlike the vast majority of WEC concepts that react against the sea-bed, a large inertia component or a submerged damper plate, Pelamis reacts against its own buoyancy. This property of ‘self-referencing’ means that the buoyancy forces caused by the waves are reacted against by buoyancy forces elsewhere on the machine itself. This has the following advantages:

— it allows structural and mooring loads to be inherently self-limiting in extreme conditions;
— it avoids the significant costs and lack of flexibility associated with the provision of an external source of reaction;
— the attendant small mooring loads allow the self-contained system to be easily taken on and off site using small cost-effective vessels; and
— the lightweight moorings are easily deployed without major on-site ‘construction’ using specialist vessels.

(ii) Selectable resonant response to wave conditions

Many WEC concepts make use of resonance to increase power capture when seas are small. However, systems that hard-wire in a resonant condition will lead to undesirably large amplified responses in storm conditions.
Pelamis uses the concept of selectable–tunable resonant response (figure 5). The joints are actively controlled to induce a cross-coupled resonant response only when desired; the default or natural condition is a benign non-resonant response inherently capable of dealing with extreme conditions. Note that, while resonance can, in theory, be achieved purely through a sophisticated PTO system in any WEC concept by adjusting the ‘internal impedance’ that the PTO applies, the use of cross-coupled resonance in the Pelamis avoids the need for excessive reactive power transfer or complicated latching systems. Instead, the simple ratio between pure damping restraints (i.e. zero reactive power) applied at each of the coupled axes effectively induces a change to the ‘external impedance’ of the machine by inducing an inclined response. The angle of the inclined response determines the natural period as dictated by the fraction of vertical hydrostatic stiffness, which balances with the inertia. This effect is apparent in internal gravity waves, in which the frequency of excitation determines the angle of inclination of freely oscillating the fluid particles. This capability to match machine response to the waves in a given sea-state is similar in concept to the now industry standard variable speed rotors and variable pitch blades on wind turbines, where the turbine speed and blade angle are continuously adjusted to optimize energy capture as the wind speed changes and avoid stress when the wind speed grows.

(iii) Smooth power

As individual waves and wave groups pass a Pelamis WEC, the input power to the individual joints is highly variable in nature, with power at a joint going from zero to a peak and back again every few seconds. Standard industrial high-pressure accumulators collect the variable input power and allow the generators to run from a slowly varying pressure supply, while coping efficiently with the very high instantaneous power levels required in individual waves. This means that all the electrical generation and transmission equipment is only rated for the average of the power available rather than for peaks. Figure 6 shows an example power record for the first joint of the prototype P1 machine during tests at the European Marine Energy Centre (EMEC) in 2007, and shows the instantaneous absorbed power along with the smooth electrical output power at that joint. The time window shown is 5 min, so the effects of both individual
waves and wave groups can be seen. The 30 min average conversion efficiency of the prototype P1 in this example was 64 per cent, with a total machine electrical output of 150kW. It should be noted that this form of power input is not specific to Pelamis, but is a feature of any wave power machine. To absorb and generate efficiently, instantaneous power levels of 10 times the average must be accommodated without excessive losses, across the whole power range. The proven Pelamis PTO allows this to be achieved.

(iv) Advanced control system with capacity to optimize

The importance of control for optimizing power capture cannot be over-emphasized. PWP has, therefore, implemented a state-of-the-art integrated control and data acquisition system to allow rapid and flexible optimization as the understanding of optimal control strategies develops with time, and as short-term wave prediction systems become available. The Pelamis PTO system allows highly efficient four-quadrant reactive power control at every joint axis based on inputs from all axes, thus allowing real-time general control of all forces with respect to the entire machine response. This is possible owing to the unique hydraulic transmission system between hydraulic cylinders and the storage accumulators that enables generalized control algorithms to be applied to optimally control the machine response for maximum absorption. Efficiency is only limited by the flow losses down short lengths of pipe and the compressibility of the oil in the cylinders. Over 30 min samples, average conversion efficiencies of up to 70 per cent have been demonstrated to date.

(v) Robustness and redundancy, fault tolerance

All critical elements within the PTO and conversion systems incorporate an appropriate degree of redundancy and fault tolerance to allow continued safe generation in the event of partial failure, and to minimize the number and severity of single point failures should they occur. This combination of reliability and fault tolerance is key to achieving reliable operation and high levels of availability for power production in the hostile marine environment and minimizes the need for and frequency of maintenance interventions. However, it must be recognized than any machinery must be maintained and maintainable. The harsh offshore environment prohibits general access for repairs and maintenance, so a method is required to enable rapid removal and installation of machines across a range of sea conditions commonly available throughout the year, as described in §1d(iv). In the event of a complete failure of the on-board power, computers

\[ \text{Figure 6. Prototype P1 Pelamis generating to the UK grid in 2007. The instantaneous absorption fluctuates wildly wave to wave, while the electrical output is a smooth average of the input. (Online version in colour.)} \]
or communication systems (a worst case scenario), a purely mechanical fail-safe system (normally held-off) takes over. If power output is overly compromised by cumulative faults, or a fault is deemed potentially damaging to other systems, then the machine can be quickly and safely removed in less than an hour with minimal vessel requirements and reinstalled again as easily. The allowable weather windows for such operations mean that they can be conducted with acceptable waiting periods throughout the year, albeit with some inevitable compromise during the winter.

(vi) **Uses proven technologies**

The Pelamis is an assembly of existing industrial components into a novel configuration. The machine requires no fundamentally new engineered component. The mechanical, electrical and hydraulics equipment have a proven track record in other applications, particularly in the offshore oil and gas sector, but also in construction vehicles and other generation technologies. The main structural elements are designed and fabricated using standard offshore and marine industry practices, thus there are many supply chain options for much of the machine, allowing lower cost competitive sourcing and flexibility in the manufacturing process.

(d) **Construction and operation and maintenance strategy**

(i) **Off-site machine build and commissioning**

All main components are readily road or sea transportable, and manufacturing and commissioning activities are carried out in a controlled factory environment reducing time, cost and weather dependence and allowing concentration of investment and resources. No offshore construction or assembly of the machine is required. Many proposed WEC systems require very large individual structures, which would need to be manufactured in a shipyard or offshore fabrication yard with attendant high overheads and reduction in flexibility (figure 7).

(ii) **Modular assembly for efficient manufacture**

The Pelamis is made up of a number of similar sections, each of which contains an identical joint assembly and PTO equipment. This allows the high-technology generation systems of each joint to be consolidated into a compact ‘skid’ that can be assembled and factory tested independently and on an open frame prior to posting into an end structure for attachment to the main tube section (figure 8). This method of assembly keeps the time that large structural components are present in the assembly area to a minimum, reducing factory size and lifting requirements considerably. A further benefit is that the entire commissioning joint PTO system can be shipped in a standard container and is therefore readily transportable to final assembly sites around the world.

(iii) **Generally deployable and scalable**

The Pelamis moorings, mid-water electrical interconnection cabling and rapid machine connection and disconnection system will allow large wave farms to be installed rapidly and cost-effectively using non-specialist vessels and equipment.
and to subsequently be expanded in a modular fashion. Current estimates are that a full mooring spread of chains and anchors can be installed in less than 24 h using existing anchor handling vessels commonplace in the offshore industry. There is no major offshore construction work or piling on-site and, owing to the deep-water location, the main cable runs do not typically need to be trenched once clear of the beach and foreshore.

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(iv) **No machine maintenance offshore: minimized weather-dependent work**

PWP is firmly of the view that the aggressive offshore environment is incompatible with any requirement for access to the machine while on-site. Even if some tasks were practical, health and safety requirements would severely limit the conditions in which any access could be gained.

It is far preferable to bring the machine to a suitable maintenance facility for complete availability of all tools, spares and skills, and to remove weather from the equation while complex procedures are executed. For this reason, the Pelamis has a proven rapid, weather-tolerant installation and removal system to allow maintenance to be conducted off-site, in a safe and properly supported environment. The system uses small, low-cost vessels to position the machine over the mooring system before an automated ‘hands-free’ winch system mechanically and electrically connects the machine to the sub-sea infrastructure.

The whole process takes less than 1 h and, owing to the hands-free nature and lack of manned access to the machine, it can be completed in rough conditions. It is immediately available to generate once installed. Removal of the machine is even more straightforward and can be completed in a matter of minutes in even rougher conditions. As Pelamis has a long, thin shape, it can be easily towed by small vessels, and its shallow draft requires only a few metres of water depth to enter sheltered facilities. A rapid installation cycle using conventional vessels and procedures is a major advantage over other marine energy and offshore wind technologies.

2. **Pelamis wave energy converter: development path**

(a) *Design tools and processes*

PWP has progressively developed a comprehensive and sophisticated set of in-house design tools and processes that are used to establish and optimize machine response and performance across all conditions and provide all required design data such as motions, loads, fatigue and wear cycles. These tools enable improvements to be made in machine designs from the fundamental geometry through to details of the PTO systems, and the creation and implementation of improved control algorithms for increased energy yield. The design tools and processes have been continuously reviewed and refined through feedback and experience of each of the machine design exercises and from operational test data.

(i) **PWP’s simulation package: ‘virtual machine’**

PWP’s suite of simulation programs has been continuously developed by PWP over the lifetime of the project and currently represents the state of the art in the modelling of wave energy conversion. The programs use a rigid body representation of the machine sections with a variety of formulations adaptable to the task at hand with respect to the computational effort and levels of detail required (table 2). The formulations include nonlinear two-dimensional hydrodynamics, three-dimensional multi-body diffraction and radiation, finite-element mooring models and fully detailed PTO and control. Linear formulations in both the time domain and frequency domain allow much more rapid computation than nonlinear models; this is very useful for design scoping.
Table 2. PWP’s suite of simulation tools. Hydrodynamic models are either three-dimensional multi-body diffraction and radiation or two-dimensional strip theory based on the relative motion hypothesis. Approximate CPU times are shown for a set of 100 wave spectra representing the sea-states for an average year.

<table>
<thead>
<tr>
<th>program</th>
<th>body dynamics</th>
<th>hydrodynamics</th>
<th>control</th>
<th>CPU</th>
<th>applications</th>
</tr>
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<tbody>
<tr>
<td>linear</td>
<td>linear</td>
<td>three-dimensional diffraction</td>
<td>linear</td>
<td>1 s</td>
<td>large parametric studies</td>
</tr>
<tr>
<td>frequency</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>domain</td>
<td></td>
<td>two-dimensional strip theory</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>linear</td>
<td>linear</td>
<td>three-dimensional diffraction</td>
<td>nonlinear</td>
<td>2 h</td>
<td>power absorption in small seas</td>
</tr>
<tr>
<td>time domain</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>nonlinear</td>
<td>nonlinear</td>
<td>two-dimensional strip theory</td>
<td>nonlinear</td>
<td>4 days</td>
<td>power absorption and survivability</td>
</tr>
<tr>
<td>time domain</td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

studies, but with loss of detail and accuracy in large waves. PWP has created a bespoke batch processing and database tool to enable large-scale design studies to be conducted in useful time scales on the company’s in-house 40-core supercomputing cluster.

The simulation has been verified by a combination of direct comparisons with industry standard tools where they exist, and also with tank test experiments and real machines. Fully directional wave spectra can be input from real wave buoy measurements to allow direct comparisons between the performance of operational machines and the simulations. Such comparisons have shown excellent agreement to date, with average power matching within a few per cent. Simulation tools are used in combination with wave resource data for given sites to provide all design inputs on annual average power output, structural load histories, mooring loads, fatigue load cycles, angle ranges, wear rates, etc. Such results are a vital part of the design verification process. The simulation is also the basis for control algorithm development, which is considered the most important route for future performance improvements. With the use of a software interface, the simulated hydraulic PTO system can be controlled by the same raw code as in the real-time machine control system, minimizing repeat work and giving maximum confidence before releasing updates onto operational machines. This is now being extended to the existing ‘hardware in the loop’ testing, whereby the Pelamis electronics hardware and firmware are both directly controlled by and also fed inputs via the Pelamis-simulated virtual machine in the wave conditions of the developers’ choice. Such an approach offers an unrivalled flexibility and confidence for testing of partial failures, including full interactions of hardware and software.

(ii) Experimental model testing

Experimental testing of the Pelamis system has developed alongside the simulation tools using a range of scale models as described in table 3. Tests have been performed in tank facilities at City University, London, UK, the University of Edinburgh, UK, the University of Glasgow, UK, Trondheim Wave Basin, Norway,
Figure 9. Snap-shot comparison between the video of the 21st scale model test in Nantes, France (b) and the corresponding animation of the nonlinear numerical simulation (a). For video/animation comparison, see http://www.youtube.com/watch?v=_f_nKSSLExw&fs=1. (Online version in colour.)

Table 3. Experimental model testing over the duration of the project.

<table>
<thead>
<tr>
<th>scale</th>
<th>date</th>
<th>control</th>
<th>test site</th>
<th>application</th>
</tr>
</thead>
<tbody>
<tr>
<td>1:80</td>
<td>1998</td>
<td>none</td>
<td>Edinburgh</td>
<td>proof-of-concept survivability</td>
</tr>
<tr>
<td>1:35</td>
<td>1998</td>
<td>water piston</td>
<td>Edinburgh</td>
<td>proof-of-concept absorption</td>
</tr>
<tr>
<td>1:20</td>
<td>2000</td>
<td>water piston</td>
<td>Edinburgh, City, Trondheim</td>
<td>absorption and survivability</td>
</tr>
<tr>
<td>1:33</td>
<td>2000–2001</td>
<td>electric motor</td>
<td>Glasgow</td>
<td>absorption and survivability</td>
</tr>
<tr>
<td>1:7</td>
<td>2001–2002</td>
<td>hydraulic</td>
<td>Firth of Forth, Nantes</td>
<td>real-time control</td>
</tr>
<tr>
<td>1:20</td>
<td>2003–2005</td>
<td>electric motor</td>
<td>Trondheim, Nantes</td>
<td>absorption and survivability</td>
</tr>
<tr>
<td>1:21</td>
<td>2007–2011</td>
<td>electric motor</td>
<td>Nantes</td>
<td>absorption and survivability</td>
</tr>
</tbody>
</table>

and at Ecole Centrale de Nantes, France, over a range of model scales ranging from 1:80 to 1:7. The model tests have provided early proof of concept, ongoing verification of the developing numerical models, testing implementations of the real-time control systems and survivability verification for the most extreme sea-state conditions. The 1:21 scale model in current use is constructed in a modular form enabling variations in section geometry and configurations to be modelled (figure 9).

(b) The P2 Pelamis

This operational experience of the P1 and the use of state-of-the-art proprietary design tools directly led to the P2 design programme culminating in:

— new joint configuration allowing for more efficient use of structure, drive train components and higher degree of modularity, making the machine easier to assemble and maintain (figure 10);
Figure 10. Cutaways of the P2 joint and power take-off (PTO) system, allowing the four hydraulic cylinders of each joint to act about 2 d.f. simultaneously. The modular PTO ‘skid’ (seen in assembly in figure 8) incorporating the generation system and low-pressure fluid reservoirs is visible between the actuators. The high-pressure accumulators used to store energy between waves and wave groups are also visible. (Online version in colour.)

Figure 11. The measured conversion efficiency of the motor-generator sets that convert the high pressure (250 bar) in the accumulators into electricity. The improvement from the previous designs applied on the P1 machines to the current P2 design can be seen in terms of both absolute efficiency and range. The total combined conversion efficiency (from wave to wire) is typically approximately 70% for the P2. (Online version in colour.)

— substantially larger joint angle range, increasing power capture and survivability margin;
— higher conversion efficiency of 20–30% and substantially lower cut in wave height (nominal 1 m Hs versus 2 m Hs) to keep absorbing in smaller seas common in summer; and
— 35 per cent higher yield from the additional cylindrical machine section and associated length, along with a 15 per cent increase in diameter.

Although all the P2 fundamental principles and design philosophy are the same as the P1, the above improvements result in more than double the target energy yield and around 50 per cent higher yield per tonne than the P1 machines (figure 11).

(c) Roadmap towards cost competitiveness

For renewable technologies to be competitive with conventional power-generating technologies in an environment without subsidies, a rigorous and well-worn path to cost reduction is being followed. The typical cost curve for...
a technology (figure 12) is characterized by cost growth during the conceptual and research and development phase as the real nature of the problem and its first-pass solution are understood and realized. This culminates in a true first-of-a-kind system, with all fundamental technical challenges encountered and resolved. From that point onwards, costs fall rapidly as the performance of the technology improves, conservatism in the design to control risks is progressively reduced and economies of scale in production are realized.

PWP has designed, built, installed and operated five full-scale machines, with a sixth due to be installed later this year; this experience gives PWP a detailed understanding of the costs associated with manufacturing and deploying wave energy technology. The P1 machines were all development units to prove the fundamental concepts and test the technology elements, and to establish design drivers for future commercial machines.

The P2 machine is the culmination of this process and represents PWP’s pre-commercial prototype for testing with customers in a commercial context. The key target for these machines is to demonstrate that the first 10 MW mini-farms will have acceptable execution risk and will deliver an acceptable return on investment in the Renewable Obligation Certificate (ROC) market currently available within Scotland, and potentially to be made available throughout the UK.

E.ON and ScottishPower Renewables will test the P2 machines at EMEC over the next 3 years. Both companies have ambitions to install larger farms of machines at sites on the west coast of Orkney, UK. Both have been successful in securing exclusive rights to develop separate 50 MW wave farms using Pelamis technology in the UK’s first wave and tidal leasing round held by the Crown Estates in 2010. At the same time, PWP itself secured the exclusive right to develop an up to 50 MW wave farm at Farr Point on the north coast of the UK. The specific wave sites awarded by the Crown Estate are highlighted in figure 13; the sites include 250 MW of unspecified technology developments.

In addition to these sites, PWP is developing two further sites in UK waters. The first, off the coast of Shetland, is being developed as a joint venture with Swedish utility Vattenfall. The joint venture company, Aegir Wave Power, was
set up in 2009 and is developing a 10 MW site off the southwest coast of Shetland, UK. PWP is also independently developing a site off the west coast of Lewis in the Outer Hebrides, UK, for a project of up to 20 MW.

References

3 Commission of the European Communities. 2010 Equitable testing and evaluation of marine energy extraction devices in terms of performance, cost and environmental impact. Deliverable D5.2 device classification template. EquiMar. See http://www.equimar.org/equimar-project-deliverables.html