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CONTENTS

ABBREVIATIONS

CfD	Contract for Difference
CoE	Cost of Energy
ETI	Energy Technologies Institute
FMEA	Failure Mode Effect Analysis
FOAK	First of a Kind
LCoE	Levelised Cost of Energy
MIMO	Multi Input, Multi Output
NPV	Net Present Value
O&M	Operations & Maintenance
P&L	Profit & Loss
P1	Pelamis P1 machine (as used in the Portuguese project)
P2	Pelamis P2 machine (as sold to E.ON and SPR)
P2e	Next generation Pelamis machine after P2 under design at time of administration
PTO	Power take-off
PWP	Pelamis Wave Power
SE	Scottish Executive
SRO	Scottish Renewables Order
TPL	Technology Performance Level
TRL	Technology Readiness Level
WEC	Wave Energy Convertor
WES	Wave Energy Scotland

1. INTRODUCTION

Developing accurate and defensible cost models for emerging technologies is both complex and involved. This report sets out the Pelamis experience with Cost of Energy (CoE) modelling, summarises the various tools developed and results obtained through the programme, and highlights the key insights it gave. It also draws conclusions and recommendations from the experience.

Levalised Cost of Energy (LCoE) modelling is imperative to justify onward development but early stage prediction of LCoE is fraught with the potential for strong *'optimism bias'* on all main inputs. This appears to be a particular problem for new wave energy concepts as the energy capture and extreme loading mechanisms and processes are very unfamiliar and unconventional. This means wave energy not only has the usual high level of uncertainty on basic cost, but also has high potential for strong optimism on yield. Seemingly competent and robust early numerical and tank models can be factors rather than percentage points out.

This report is written to provide insight into how the Pelamis models and projections moved and developed with time and with progress of the technology up the TRL scale. The information is captured here to provide assistance in assessing CoE projections for new or earlier stage technologies and to help ensure learning from this experience is realised.

An introduction and timeline of modelling techniques used, how they evolved into a comprehensive set of economic modelling tools as experience with real full scale machines was gained, and through how initially optimistic projections become progressively more realistic. Also provided is a high level description for the primary set of economic modelling tools produced with and for utility partners and how they were validated with real machine data and the experience gained from them. The level of validation of the various inputs is summarised alongside the resulting error bounds. Where appropriate, this has been generalised to form a recommendation for confidence bounds in similar calculations.

A set of simplified models produced for the *Energy Technologies Institute Wave Energy Converter* ('ETI WEC') project is also discussed. These models were expressly produced to allow robust comparison of different technology and machine size options without the complexity of the aforementioned models.

1.1 BACKGROUND

All new technologies go through a familiar development and maturing process. For energy technologies cost of energy is generally the most important consideration. A typical plot of how cost varies as cumulative capacity is increased is shown in the graph in Figure 1 below. Typically, early estimates of cost prove to be optimistic and costs rise to the point that a 'First-of-a-kind' or FOAK system is successfully demonstrated. Thereafter, there are many opportunities to reduce cost and increase performance during a period of initial 'rapid learning' before the rate of learning progressively slows as the technology matures.

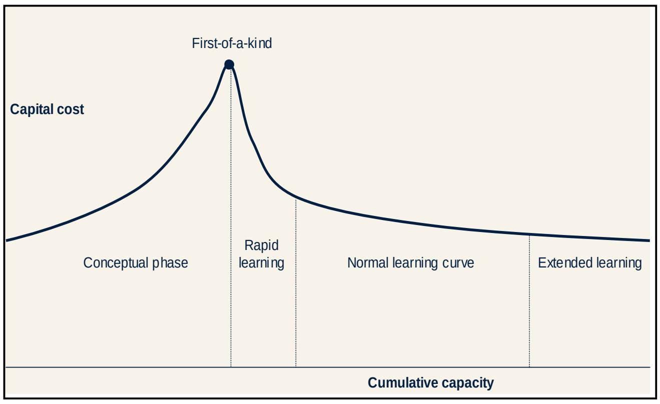


Figure 1 – schematic representation of the technology learning process

Cost of energy projections are core to the short and long term viability of any energy technology. Cost reduction curves have been researched and derived for many energy technologies, examples of data from other sectors are shown in Figure 2.

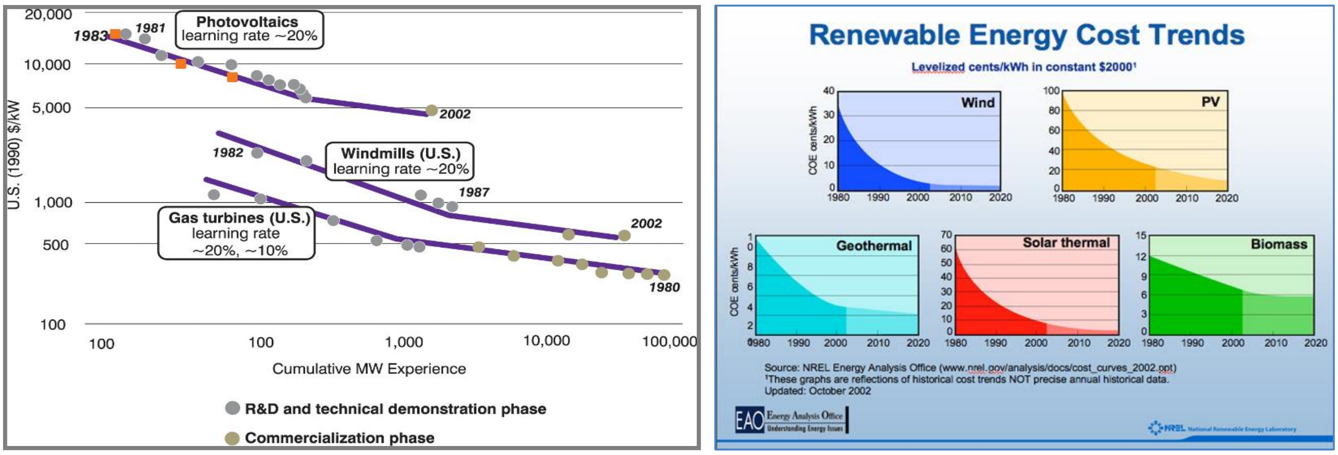


Figure 2 – examples of cost reduction profiles in other energy technologies

All new technologies will learn through experience and increase production volumes. It is critical new technologies can show a clear track to cost convergence with other similar methods of power generation. Much research and analysis has been carried out into experience in other sectors and what it means for the prospects for new technology.

One example PWP called upon many times through their development programme was some excellent data from the Danish energy research centre RISO concerning the early stages of development of the wind industry. A couple of example plots from this are provided in Figure 3 below. They clearly show how wind energy successfully delivered rapid cost of energy reduction through a blend of innovation and deployment. Step LCoE reductions were delivered through introduction of innovation in relatively short product life cycles and learning by doing through production optimisation and deployment scale.

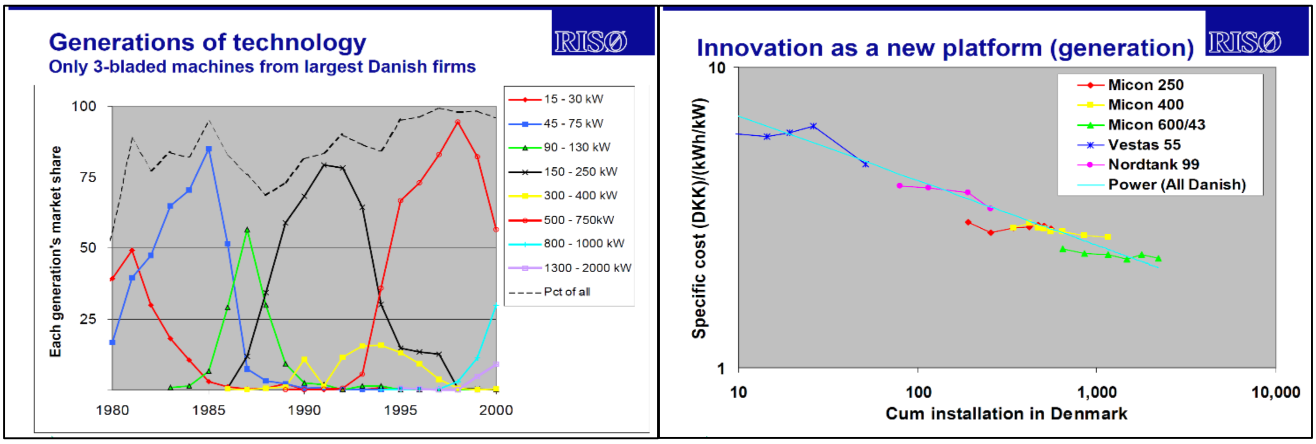


Figure 3 – wind energy cost reduction through mixture of innovation and volume (Source: Joint EU/IEA workshop on Experience curves: A tool for Energy Policy Analysis and Design, Paris, IEA, 22 – 24 January 2003, Per Dannemand Andersen)

Study of past precedents in cost reduction and performance enhancement are useful and informative to developing plans and projections but blind application of simple underlying learning rates on initial forecast cost and yield can lead to large errors in forecasts. It is only through carefully understanding the issues and drivers, how they relate to a particular new technology, and how tools can be robustly validated in context that sensible forecasts can be made.

1.2 THE ROLE OF LCOE MODELLING IN THE PELAMIS DEVELOPMENT PROGRAMME

PWP created, evolved and refined an extensive suite of cost of energy modelling tools and data. Third party input, review and major validation programmes were carried out throughout this process. The PWP LCoE modelling programme therefore represents an extremely interesting case study on development of these models as the technology advances through the TRL scale. In order to lean from the Pelamis experience, it is important to understand where the models proved to be accurate and inaccurate, and why. It is equally important to understand what conclusions can, or cannot, be drawn from models at each stage in the development path.

The main uses of LCoE modelling in PWP were as follows:

- Private investment driver – a key element of investor due diligence at all stages was the opening LCoE and subsequent trajectory to demonstrate that a 'profit pool' exists for investors in the technology and projects. Ability to demonstrate and justify rapid LCoE reduction was vital as it would have allowed the profit pool to grow if a lead on the rest of the sector could be delivered and maintained. This provides the fundamental drivers and a clear early mover advantage both of which were critical to securing investment.
- Customer due diligence – similar to the above but more focused on specific IRR of early projects. From an early stage PWP adopted the approach of 'shared project models' with customers and other stakeholders. This established a language for reviewing where PWP were and what needed to be delivered by an onward programme. These models were simple in the first instance but the tools grew to become sophisticated full models including uncertainty on all factors. Each entry or assumption was discussed and agreed amongst all parties. This included costs, resource, yield, availability and more. A model and process of this sort can be extremely beneficial to help create transparency and confidence.
- Public sector investment/policy work – it was key that policy initiatives were constructed to deliver the right pull for investment without over-incentivising. A considerable amount of LCoE modelling was therefore directed at benchmarking using standardized models for grant applications (e.g. Marine Energy Challenge, Marine Energy Accelerator, Marine Renewable Commercialisation Fund etc.).
- Driving technical progress – much effort was made at PWP to use LCoE to drive technology choices. Often this was in the context of the above points so decision making progress metrics were skewed, but in the final 2-3 years through the ETI project and subsequent work, truly objective assessment of options and configurations were made. This provides a great model for a more generalized 'optioneering' methodology for the sector.

1.3 ISSUES ASSOCIATED WITH RELIANCE ON LCOE MODELLING

While making LCoE analysis a focus of the development process is an essential thing to do, there were some unintended issues and pitfalls. These are discussed briefly below.

- Sole and exclusive focus on LCoE is potentially dangerous. PWP definitely fell into the trap of chasing customer IRR targets on first projects rather than keeping technology steps manageable. There is a right compromise between driving technology to suit finance and driving support policies to meet the needs of emerging technology. This is an area where Quoceant believe there is room to refine the approach further if the sector is to make it into commercial deployment.
- Sophisticated and robust projection of LCoE in the 100-1000MW range is key to justifying continuing progress, but it should not be the key determinant of the viability of the technology at the first subscale projects.
- Drivers for new tools should be focused on using results from RD&D to project central estimates and uncertainty bounds for 100 and 1000MW deployed rather than just the first 10MW demonstration array.

The primary role of the first 10MW array should be to confirm assumptions and dramatically reduce the uncertainty bounds on the next stages rather than to deliver a major financial return in itself. While this was the objective of the LCoE modelling focus, it is all too easy for all parties to get caught up chasing the nearer-term ball as the critical near term existential stage gate. The fall of PWP was actually largely at the earlier hurdle. The cost of getting through the first projects to 20-30MW operating was deemed to be too high.

1.3.1 OVERVIEW OF MAIN LCOE INPUTS AND THE POSSIBLE PITFALLS

Early stage prediction of LCoE for wave energy converters is very difficult and fraught with the potential for strong *'optimism bias'* on all main inputs. This bias, even in the face of significant R&D effort, creates a key problem for the industry in that it invariably makes earlier stage concepts look hugely superior to higher TRL systems. While this is the case in all sectors to a degree, it is particularly acute in wave energy.

The Pelamis experience can teach a lot about the requirements and pitfalls of LCoE modelling. Initially, as with many new technologies, there was a great deal of uncertainty around many of the main cost of energy assumptions. Through the 17 year PWP development programme it was possible to model and understand the majority of these uncertainties and drivers. PWP believed that, in the end, a good level of confidence over LCoE model inputs was achieved.

Examples of some of the areas where an insight into possible major errors are likely in early estimates for new systems and machine designs are as follows:

- Yield – generating realistic estimates of yield is hard! Highly developed and complex numerical and tank models are required to get traction on this and deliver robust results. Initial over optimism is very hard to avoid, and factors rather the percentage level errors in LCoE are likely. Indeed, the Pelamis programme showed early projections can be factors out even with credible resource, hydrodynamic and PTO models. There are range of real world factors which have a detrimental effect on yield that are easy to overlook.
- Capex – again, it is easy to be factors out here. PWP were initially overoptimistic about amount of steel required, allowable stress ranges etc. and also initially placed a lot of confidence in 'off the shelf' bearing technology which proved to be unfounded. The main issue here is you don't know what you need until you try to do it! This is an area where there is a need to put real machines to sea to begin to assimilate the experience and data required to make realistic Capex projections for realistic engineered solutions.
- O&M and availability – there is a huge tendency to use a simplistic approach here but the complex interactions of reliability and weather windows are not necessarily easy to predict. To address uncertainty in PWP's assertions about availability, the optimal O&M strategy, and costs, PWP committed to developing an 'O&M model'. It uses a *'system-effectiveness'* approach to determine how reliable subsystems need to be, and what the costs and weather limitations are on fixing issues. Quoceant believe it essential to adopt at least this type of approach to have any handle at all on likely O&M costs and availability. While capex and yield models in other marine energy technology are becoming better founded, to our knowledge O&M costs and availability are still very poorly addressed in the marine energy space.
- Learning rates – aside from yield perhaps the biggest area of optimism bias creeps in with the introduction and then blind reliance on simplistic learning rates, in many cases perhaps before it is reasonable to do so. Learning rates are a good indication of what a successful sector can achieve but reductions can only be delivered in the near term through specific, tangible steps in the technology and through demonstrable sharing of fixed costs and economies of scale etc. In PWP's earliest models an assumed learning rate was applied directly on LCoE from the first machine forwards. However, it was quickly realised that this was not realistic and later models used a hybrid approach to learning rates.

2. DEVELOPMENT OF THE PELAMIS MACHINE AND LCOE MODELLING TOOLS

2.1 EARLY MODELS

PWP's first cost of energy models were developed in 1998 for the company's Scottish Renewables Order (SRO) – Round 3 tender submission. The tender required a full cost model to be produced to justify the tariff applied for. A competent but early stage model was created for the purpose. It had the following features:

- It was based on the customary basic *NPV(costs)/NPV(yield)* approach;
- A discount rate / IRR of ~6% was used (this was customary for utility infrastructure projects at the time);
- Yield inputs to the model were derived from detailed numerical simulations. This numerical simulation was, at the time, the subject of some simple validations using linear tank test models;
- Basic load requirements for the power take-off system were also derived from the simulation. A basic structural design was then completed using stress ranges more akin to the civil engineering sector;
- Costings were obtained for all components including a detailed structural costing and quotes for many of the main power take-off elements;
- Availability assumptions were based on experience in wind energy at the time;
- O&M costs were based on occasional manned access in calm weather for maintenance and repair without any operational experience or reliability modelling to back it up.

Given the analysis it was built on, PWP believed it was (at the time) reasonable to assume that the model had hit the '80-20' rule in terms of cost confidence. With a degree of 'iteration' these models came out with a bid cost of energy of 7.1p/kWh in 1998 prices. The bid was successful at this price which triggered the next round of development work.

After much discussion, lobbying and negotiation, the UK restarted a limited wave energy R&D programme in 1999 and PWP secured their first project from this in 2000. The project was to complete a more thorough assessment of Pelamis designs and cost of energy. A similar analysis and costing was completed with improved tools, tank models, and designs and analysis. More detailed designs were produced and costings for machines were a mixture of budget quotations and application of costing rules and metrics in a similar way to that used by civil contractors.

At this stage, a cost of energy learning model was created using learning-rates applied to cost of energy. Rates were chosen to be the same as many early technologies including wind energy. Opex and availability assumptions were considered a little more thoroughly but were still based on very high level assumptions.

As shown in Figure 4 below, these models projected opening costs of 5-6p/kWh (2000 prices) reducing to 2-4p/KWh after 10GW or so installed. With various progressive extensions and improvement these models were adopted for various business development purposes leading to PWP winning a tender process from Canadian Utility BC Hydro to develop a farm off Vancouver Island. The models also formed the basis for underpinning due diligence, leading up to the 2002 £6m Venture Capital investment in the company following demonstration of the technology at 7th scale in 2001.

Around this time the first shared project model was created between a consortium of PWP, ScottishPower and AMEC. This brought in detailed and robust treatment of other project costs such as pre-development and consenting, grid connection and use costs, through life costs estimates for all elements rather than simple annualised estimates, decommissioning costs etc.

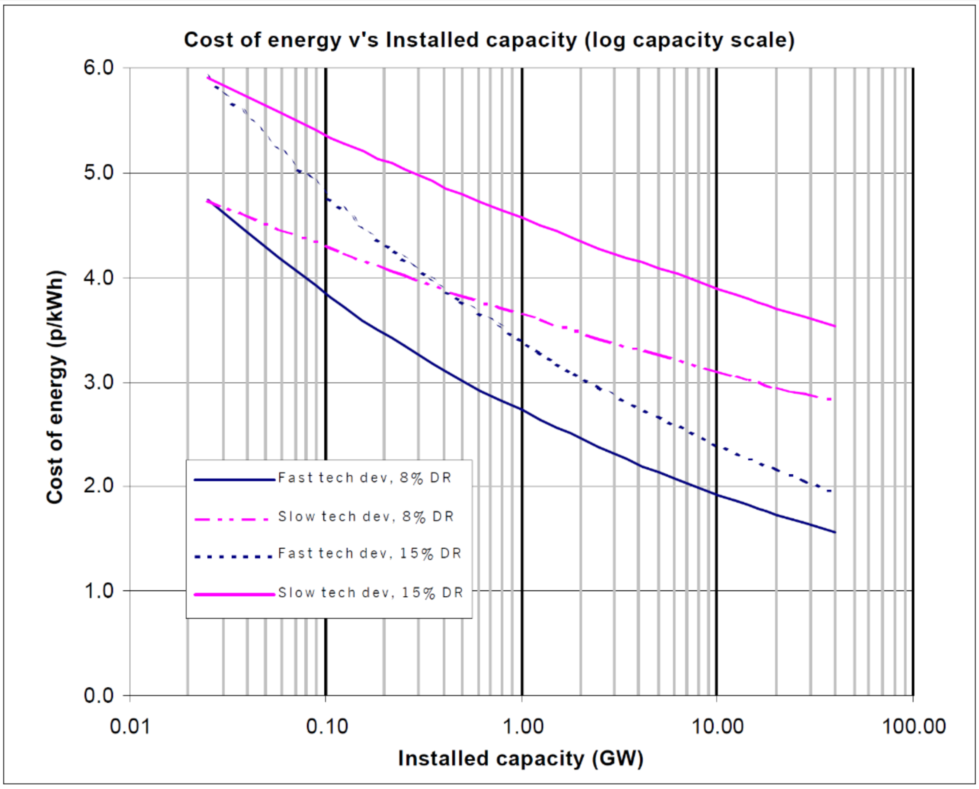


Figure 4 – example results from LCoE work in c.2001 showing very attractive opening position and a range of reduction scenarios. Costs are in p/kWh in 2000. As a very crude approximate guide multiply by ~1.5 for 2016 equivalent but this is approximate only as machine cost strongly linked to steel price and other commodities etc. These projections were based on what PWP believed to be thorough assessments of all main inputs/assumptions but of course turned out to be highly optimistic as is often the case in early stage development estimates.

2.2 INITIAL FULL-SCALE VALIDATION

The 2002 Venture Capital investment was to fast track the development and demonstration of the technology through to an intended AIM listing in 2004-5. A key focus was to validate the assumptions in the LCoE modelling underpinning an aggressive roll-out plan in the business plan at the time.

The centrepiece of this programme was the rapid design, build and demonstration of a real full-scale machine at EMEC in Orkney which was being hurriedly built to support the Pelamis and other WEC programmes. The Pelamis full-scale prototype programme remains one of the most extraordinary projects in the sector. For a little over £5m (2004 prices) the world’s first full-system offshore wave energy converter was designed, built, deployed and commissioned.

The machine was intended to be a true prototype for serial units but in the end, while it fell seriously short of achieving this, it still represented a massive single step forward for the sector, and was certainly one of the most cost effective ones. The machine and mooring design was, for the first time, verified against offshore oil and gas codes and standards in terms of survivability case, intact and damaged integrity, fatigue and corrosion design etc. and the machine and moorings was procured and built to appropriate standards. PTO systems were no longer idealised numerical approximations but real engineered systems developed in the laboratory with the supply chain and then specified for the real machine. Control systems dealing with real world latency, stability and gain limits, and distributed remote control issues were developed and demonstrated. All of this meant that Capex increased and yield dropped markedly, a reality check for those early LCoE estimates. These projections were incorporated to into similar LCoE models which showed that while the impacts were strongly negative, opening costs still looked acceptable.

The LCoE models incorporated experience from the full-scale prototype and new cost curves were developed to create a more realistic and informed business plan. This led directly to the lobbying for support for opening cost of energy in the region of £250-300/MWh (2005 prices), a similar starting point to wind energy in Denmark and similar to the then projected opening costs of solar PV. These models were the basis for proceeding with the stage 1 project at Aguçadoura in Portugal and for building the case for an AIM listing of PWP to provide the capital required to deliver the next stage. The project with Enersis promised a 500MW staged deployment with tariffs to support, if the first 3 machine deployment could be proven to work (non-commercially) for 12 months or so. This was a huge prize for the technology and one that would have pretty much guaranteed strong financial backing and so created a very strong draw for all stakeholders.

By this time Capex estimates were projecting more realistic opening costs of ~£3m/MW installed (pre-project development and balance of plant etc.) falling rapidly to ~£1.5m/MW which is where offshore wind was forecast to open up at the time.

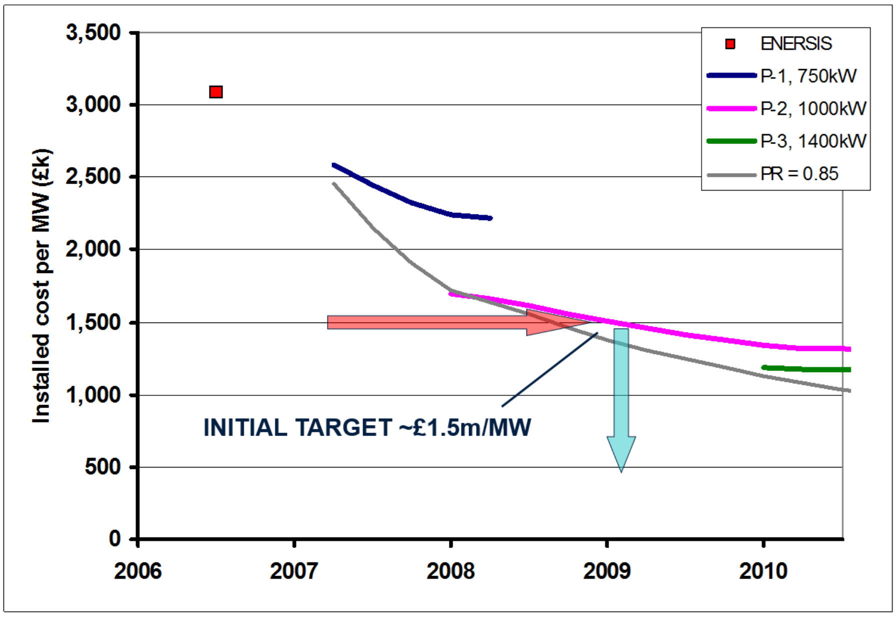


Figure 5 – Installed cost per MW estimations pre-Aguçadoura project

2.3 FIRST 'REAL' VALIDATION

The Portuguese project was contracted before a more thorough set of trials were possible on the prototype machine in Orkney. Restricted finance, application of all PWP's resources to Portugal, and a spike in vessel prices in the North Sea all contributed to a hiatus in testing in Orkney through 2005. It was not until 2006/7 when it was realised that further experience with real operations, and in particular with remote moorings connections with small vessels, needed to be secured that the prototype programme in Orkney was revived and refinanced. This proved to be one of the most important phases of operation in the PWP programme on three counts:

- It provided a longer term operation and experience in a wider range of sea-states allowing better validation of performance models. With all 'real world' effects understood and a more realistic use of available joint angle range the yield estimates from the 'P1' system was more than halved. However, with these assumptions applied to the now fully non-linear numerical models, agreements in the sub 10% error range were achieved for operations at sea across a broad range of conditions.
- While no major damage was done, responsible staged testing in increasing conditions showed that original survivability design criteria based on individual extreme waves were not sufficient in terms of joint angle and load ranges. This resulted in a full review of the design and the third party survivability verification process.

- It proved the necessity and then efficacy of the 'hands-free' mechanical and electrical connection system, and real experience of the limits of this could inform O&M and availability models for the first time.
- It showed that assumed robustness, durability and reliability were unrealistically high with the current technology, and that relying on the supply chain to provide off the shelf solutions to very high-level specifications was not adequate in many areas (most notably in 'simple' sea-water lubricated bearings and in conventional oil filtration approaches etc.).

The result of this phase was a further rebasing of opening and future LCoE estimates, this time taking projections above what was deemed as acceptable for the first time in the programme's history. The Aguçadoura 1 project continued and, despite many problems and setbacks, was successfully commissioned in October 2008 just weeks ahead of the 2008 financial crash that was to spell the end of the AIM exit route and thereby the Financial Venture Capital funding model.

2.4 FIRST 'REAL' MACHINES

With the experience of the first generation 'P1' machines in Orkney and Portugal PWP came to three key conclusions for the onward programme:

- Hitting the realistic opening cost of energy targets that had been set and had now been implemented in policy would require more advanced technology and larger machines than had originally been envisaged.
- Survivability criteria needed to be completely reassessed for future machines including partial failure cases in the PTO and other systems etc.
- A major programme was required to source, develop and validate solutions to the key durability and reliability issues exposed by the P1 programme.
- A much more thorough understanding of Opex and availability drivers and sensitivities was required to guide and prioritise the technical programme.

PWP had been working with several utilities for a number of years and were fortunate to have forged particularly strong links with both E.ON and SPRby this stage. While the experience with the P1 machines had shown that more work was required, it had also shown that a Pelamis form machine could be built and safely operated, and that it could generate power to the grid.

From this knowledge base, PWP discussed alternative ways forward with our prospective utility customers and this is the point at which the LCoE models started to really drive the development process rather than be a key metric and tracking tool. With the Capex/Opex/Yield experience and known residual knowledge gaps a number of options for the onward programme were created. This included, scaled up 'P1 form' machines but with much more joint angle available for both power absorption and survivability, and a new 'P2' universal joint configuration that promised to address some of the reasons why yield had fallen very short on original projections due to limited control resolution. The initial 'system effectiveness' review of Opex and availability requirements was extended into a more sophisticated tool to produce the first proper Monte Carlo driven models of the 'cost of availability' with realistic assumptions on lost revenue, waiting on weather, vessel costs, and costs to repair etc. The basis for comparison of the options were various shared LCoE models with supporting 'viability' assessments including third party due diligence exercises.

Ultimately, it was agreed that the best option was a new P2 configuration machine and PWP agreed to supply them with a test unit for trial sat EMEC. A contract for this was signed late in 2008, just before the financial crisis hit.

Pricing for the contract was based on a basic extrapolation of the Capex costs of the P1 unit. The P2 design was only at the 'advanced concept' stage when the contract was signed and PWP were only learning about technical issues with water lubricated bearings and joint angle limits from P1 machine in Portugal at the time. A high level analysis of the likely scaling and technical changes was carried out and used the P1 costs list to create a representative parts list and costing for the P2 machine. Also, assumptions were made about the fact that other P2 orders were expected to come in from ScottishPower and other interested parties. There was initially a high level of confidence in this cost model as it was based on real experience with P1 but the level of engineering and change required, and the limited time and resources available to do, so meant that costs escalated during detailed engineering and procurement. Main cost centres affected were:

- <u>Structures</u> – a number of factors conspired to result in a major error in specification of the main structural elements. The P1 design was actually more structurally efficient than it had been given credit for, load-paths were simple and efficient and inherent structural stiffness was high. In the time available the P2 structures used a disproportionately higher weight of steel and resulted in a less stiff structure (also an issue for yield projections). Steel prices had risen sharply in the intervening years and this had only partially been accounted for. Finally, it became clear that for the more complex end structures there was an element (perhaps 10-20%) of optimism in rates per tonne from the fact that supplier of the P1 units had held prices as low as they could through the build programmes to help us get off the ground and of course to try to secure an onward role in the business. There were careful attempts to try to avoid or account for this but it undoubtedly remained a modest factor.
- <u>Bearing systems</u> – with the unsuitability of simple 'off the shelf' seawater lubricated approaches exposed by the P1 programme PWP partnered with leading bearing supplier Schaeffler INA for the P2 project and committed to fully isolating all critical mechanical components from sea water. Resulting costs in implementing the bearing system spiralled and added over £750k to the cost of the initial P2 machine.
- <u>Hydraulic cylinders</u> – in association with the bearing system noted above and greater and greater ultimate joint angle requirements the rams needed to be redesigned to deliver a much higher stroke and larger peak loads. As a result, the font rod diameter increased by over 50% with resultant growth on bore diameter to compensate and the knock on effect that ram costs increased markedly.

The process was a good example of where assumptions and robust cost data for one application cannot always be readily transferred to another and that no projections can cater for gross change of the engineering solutions applied. However, the focus of the P2 project was on demonstrating success so it was resolved to continue, somewhat side-lining LCoE for the sake of progress at this stage. This said, pressure to minimise cost-increase was intense and a number of major changes were made to the machine to reduce cost in the short term. The main one was the removal of 'lobes' to create a non-circular cross-section to increase machine volume and roll stability to underpin much greater yield (order of 25%+). This proved critical in later stages of assessment of the potential of P2.

In parallel with build and operation of the first P2 unit for E.ON discussions and negotiations continued with ScottishPower Renewables (SPR) and commenced with Vattenfall. SPR agreed to partner with E.On and build a basically similar but improved P2 unit to test alongside the E.ON machine. The adapted and improved LCoE model were still relied upon at this stage. Despite the cost growth in P2, the case remained adequate for SPR to place an order for a similar but somewhat refined machine early in 2010, critically before the E.ON machine has commenced testing.

With only a few months to work on improvements and refinements to P2 design for SPR unit, the opportunity for cost reduction was limited. However, a number of major steps were made, notably in the main structural end caps, main tubes, and bearing systems. Overall the second P2 machine was delivered for almost 15% less than the first unit. In addition, the second machine allowed the trial of alternative bearing technologies and improvements to the PTO and control systems. In hindsight, it would have been more valuable to technical progress if a few thousand hours of operation between the two P2 machines was possible. However, there was intense internal pressure to have a further order to drive the new trade sale based exit strategy of the shareholders.

2.5 EMERGENCE OF MORE COMPREHENSIVE LCOE MODELING TOOLS

While the eventual performance of the P2 machines fell significantly short of target, and survivability margins were exposed as still not being adequate in all circumstances, the engineering solutions employed generally worked very well. Each machine clocked up some 6,000 hours at sea in a wide range of conditions up to 5m Hs, and generated a roughly equal proportion of a total of 250MWh of electricity. All systems work effectively and the vast majority worked reliably and efficiently. With only a very few surmountable exceptions, experience on the programme was that all main systems and design processes were now fit for purpose as the basis for a production machine. This provided a new solid foundation for the next stage of development of the PWP LCoE modelling tools.

The interest of Vattenfall grew stronger through 2010/11 and they funded a series of very intense and thorough due diligence processes in the sector. Pelamis was picked as a leading technology in the sector and one suitable for near term array demonstration. They adopted a very open and hands-on approach to development work compared to previous experience.

It was concluded at this stage that a completely revised set of LCoE models covering Capex, Yield and Opex and learning models for real project examples through to full commercialisation was required. This approach allowed focus on the most important aspects for initial arrays, while keeping development very much in the context of ongoing rapid learning and cost reduction. This set of models was continuously evolved and developed for the next 3 years and remained one of the main tools for detailed economic assessment up to the company entering administration.

2.6 PWP'S FINAL LCOE MODEL SET

In 2011 the two P2 machines were built and the first operational results were coming in. After a number of teething problems, more sustained operations started in 2011/12. It was clear that, while the machines were on the whole operating very well, both performance was below what PWP had projected prior to contract and, after a few trips in rough conditions, the survivability margins of the system were also an area of concern. This was particularly true if the Pelamis encountered unusual combined wind/wave/current conditions and/or there was a failure of some key on-board systems. From this it was clear that PWP needed to both build on the successes and address the shortcomings of the P2 design and programme in order to get to financial close on initial arrays to kick-off commercialisation of the technology.

As mentioned earlier, Vattenfall had, with their strong in-house engineering capability, started a very intensive and hands-on due diligence and technology assessment process. Vattenfall focussed all of their efforts on researching and optimising a 10MW array in Shetland, known as Aegir, with a 50MW expansion phase on the same site thereafter. This project focus provided the basis for a complete recast of the main LCoE projection tools. New Capex, learning, and project models were created, and the already sophisticated Opex and availability tools were further extended and better validated. Yield tools in particular were scrutinised extended, optimised and thoroughly validated with real at sea experience to give the best possible confidence in projections, and latterly a major piece of work on the ultimate absorption potential through advanced control was included.

The tools were used to complete a wide ranging 'optioneering' exercise to determine machine geometries and designs that could meet both the short term needs of financing the initial 10MW array and be the 'correct' basis for commercialising on the basis of longer term LCoE reduction potential. PWP built and agreed models for modifying, scaling up and optimising the P2 system. More robust survivability criteria to ensure that future machines would hit the 'critical compromise' between economics and survivability were defined and agreed. Additionally, PWP completed in depth studies of major technical alternatives like concrete as a material and alternative PTO configurations. Extensive geometry and control optimisation studies validated in the tank and latterly with real result from the P2 machines in Orkney to underpin realistic improved yield figures were also undertaken. Electrical architectures, voltages, design and levels of redundancy offshore to come up with the best options for initial and larger wave farms were considered. On all this PWP engaged closely with the customers, partners and supply chain to build the case for progressing to the first arrays.

All in all, this was an extraordinary and unprecedented (in the sector) level of analysis, validation and understanding for a WEC configuration and design architecture. Ultimately, it is thought that it by and large removed the potential for optimism bias on the projections at a time when others in the sector remained heavily optimistic.

Later in this process a £1.4m contract from the Energy Technologies Institute to push the boundaries further was won. This work pushed the innovation and optioneering boundaries beyond what would have been acceptable to the utility partners alone and allowed a much wider range of options to be considered for initial and future machines. This broader remit led the requirement for a higher level and simplified set of tools to allow efficient assessment of LCoE impact of technology options.

With the success in securing a technology optimisation project from the Energy Technologies Institute in 2011/12 PWP exposed one limitation of the full project model based LCoE tools – it was very laborious and time consuming to objectively assess a large number of options and configurations. Therefore, for this purpose a much lighter weight LCoE model was built. This model read in detailed machine option capex and yield projections from the main models but then used lumped costs and values for other project development and balance of plant, and reverted to a simple *NPV(costs)/NPV(yield)* calculation to allow simple direct comparison of a large number of machine configurations and options. The simplified project model was checked against the comprehensive tools and found to be within 5-10% which was deemed adequate for the purposes of relative assessment of options.

This final set of models was the state of the art at the time that PWP entered administration. New machine and commercialisation options were continually generated and reviewed using them and they became the core decision making and tracking tool for the company.

2.7 SUMMARY & DISCUSSION

With all of the experience in conceiving, developing and refining the various LCoE tools described above PWP, and now Quoceant, have a unique insight into what is the most appropriate and useful methodologies for future projects and technologies. These points can be summarised as follows:

- The tools developed and used should be very much tailored to the stage of development and TRL of the candidate systems. In the early stages PWP often placed too much emphasis and reliance of projections of cost and particularly yield when planning development work and machine builds. There is a serious risk of creating projections that are at best misleading and at worst meaningless unless the basic engineering specifications and system architectures have been properly defined and demonstrated in real conditions.

- Models can only project into a finite ‘sphere’ around the assumptions used to generate the primary inputs. The best example PWP had of this was the major cost growth experienced from P1 to P2 caused primarily by the need to engineer in more motion and load, and to provide radically different bearing solutions.
- It is very tempting to use models that are well validated in one area to stray into an area where they don’t apply in pursuit of a more attractive opening cost of energy. This is true particularly of scaling up. While a modest degree of scaling up using a set of data from another scale is appropriate is ok, we need to be very careful taking this too far. All new technologies want to start as far along the technology development curve as possible to minimise the time and cost of commercialisation and to maximise return to all investors. The problem arises where steps from the proven realm are too large and in effect negate progress up the TRL & TPL scales due to engineering solutions and cost that were appropriate for a certain size and design becoming invalid for a new set of assumptions. Most sectors have fallen foul of this problem of course, overstretching from a position of initial confidence.
- Creating and evolving dependable technology learning models is a very difficult process. From the technology push side – if PWP had known the ultimate technical solution at the start it would have been developed then. The whole process of innovation requires experience, time, talent and investment to yield results.
- Making assumptions about innovation and its impact is difficult but must be done or any projections will prove to be woefully unambitious for early stage technologies.
- Volume learning effects must be treated differently – here it is more about the quality of data from volume manufacturers. In essence volume learning can and should be separated from technology innovation, with inputs and assumptions coming from very different sources and for the most part being largely independent of each other (aside from changing basic technology areas of course). We believe that the staged approach to learning that PWP used for the comprehensive set of models was very sound, but we would refine it further to even more explicitly separate innovation and volume elements.

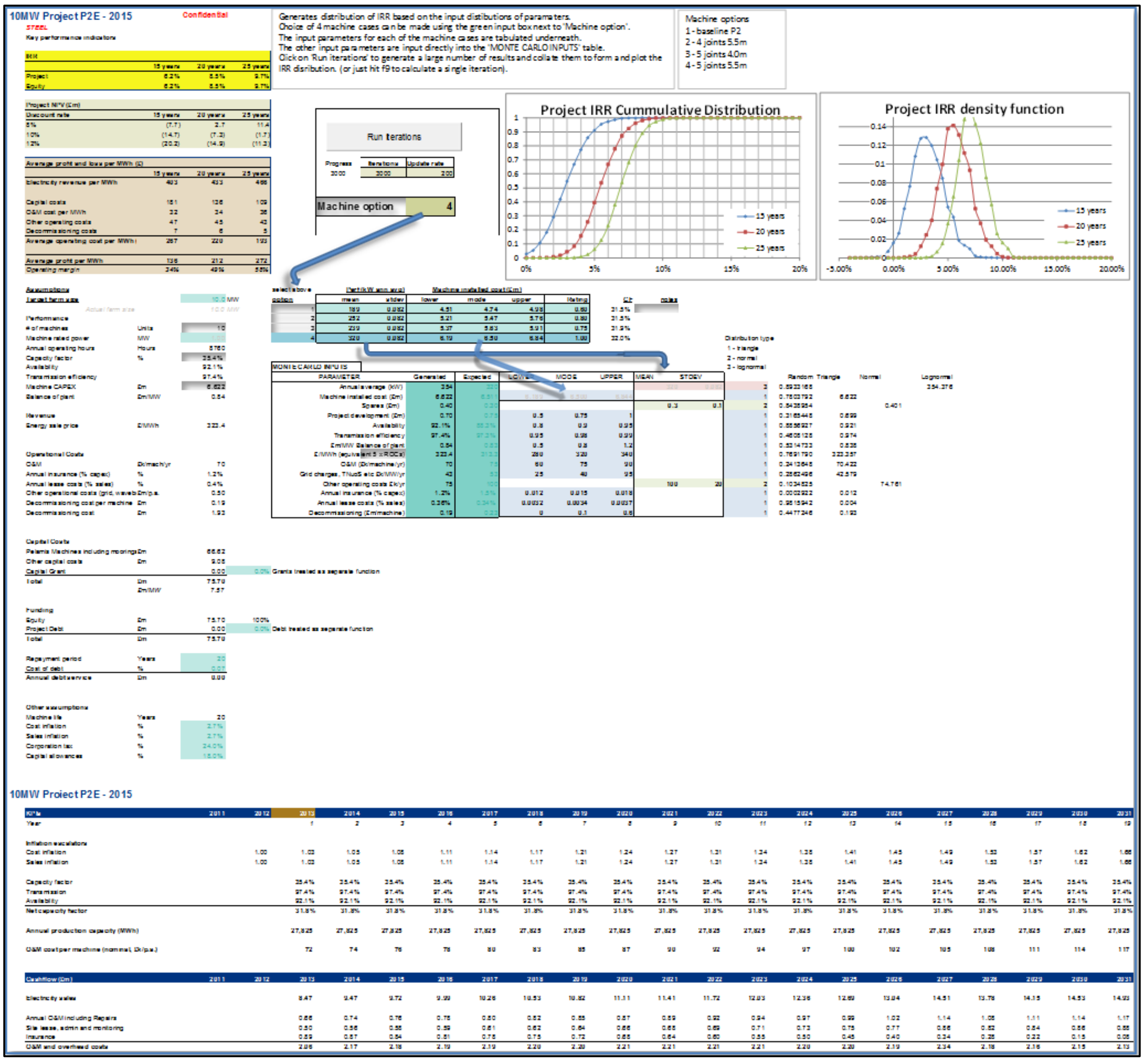
3. PWP'S COMPREHENSIVE LCOE MODEL SET

In the context of the background set out in the previous section, PWP's LCoE modelling tools were significantly enhanced and refined in a process that began in 2011 and was continuous up until the point of PWP entering administration in 2014. This process was undertaken with significant input and consultation with PWP's utility partners. The final set of models was the state of the art at the time that PWP entered administration. New machine and commercialisation options were continually generated and reviewed using them and they became the core decision making and tracking tool for the company. The modelling approach, their workings and any assumptions are set out in the following sections.

3.1 OVERVIEW OF THE PROJECT MODEL

The project model brings numerous inputs and factors together to determine the cost of energy for a given IRR, or the IRR of the project for a given available price of energy. The model includes assumed distribution forms and widths for all parameters to allow uncertainty to be modelled as well as the central estimate. Inputs are specified by the user (and are often the results form other more detailed models), and different profit margins, grant intensities, debt-equity ratios, tax regimes etc. can be included.

The model uses a Monte Carlo method to determine the distribution of IRR about the expected value using the range of each variable. This analysis assumes that all the key variables are independent but it was believed this this was a valid assumption, and this view was supported in various due diligence exercises.



10MW Project P2E - 2015

Generates distribution of IRR based on the input distibutions of parameters.
Choice of 4 machine cases can be made using the green input box next to 'Machine option'.
The input parameters for each of the machine cases are tabulated underneath.
The other input parameters are input directly into the 'MONTE CARLO INPUTS' table.
Click on 'Run iterations' to generate a large number of results and collate them to form and plot the IRR disribution. (or just hit f9 to calculate a single iteration).

Machine options
1 - baseline P2
2 - 4 joints 5.5m
3 - 5 joints 4.0m
4 - 5 joints 5.5m

Figure 6 – Screenshot of the main project model input/output frame.

The key inputs of the model are:

- All input variables have assumed distributions with defined form and width. This allows the Monte Carlo calculation to generate probability distributions of IRR and other variables.
- Four 'machine types' can be defined and selected from (allowing the user to define and choose different machine configurations, e.g. 4-joint vs 5-joint etc., on which the model is run).
- Yield and machine installed cost information is entered including ranges for the costs and an assumed standard deviation for the yield. A lognormal distribution is used for the yield estimates as this was found to best fit the data from analysis.
- A number of other project variables (e.g. transmission efficiency, grid charges etc.) are entered with different distribution forms selectable.
- Project size, capital grants available, debt funding included, and various global variables such as inflation rate, tax regime etc. can be specified as appropriate for the project developer.

The full project model implemented for the inputs specified above evaluates the project cashflow, P&L & Balance Sheet, and completes a tax computation. A range of project performance indicators are calculated, the main one of these is the IRR over various return periods.

The model runs a Monte Carlo loop for the number of iterations specified. It builds 15, 20 & 25 year Project IRR distributions and displays these results. Other plots such as Equity IRR (in the case of debt funding) and probability density functions are also available if desired.

The tool is a flexible and interactive way to assess the fundamental project economics of various options and scenarios, and an invaluable tool for ascertaining confidence levels and key sensitivities in the LCoE calculation.

3.2 OVERVIEW OF MODELLING APPROACH

The key modelling approach used by PWP in the development of this model was to ensure uncertainty was properly dealt with. This meant every input or assumption was subjected to an appropriate level of scrutiny and validation, including agreeing the residual uncertainty bounds. Incorporating this uncertainty into the model resulted the project model that subsequently formed the heart of PWP's LCoE modelling tools.

The main functionality that was required in this project model was the ability to review sets of machine options in terms of their impact on project 'IRR'. To achieve this in a usable form the majority of the inputs into the main project model actually had their own, more detailed, option models created and reviewed. These more specific models generated the high level specific cost and performance inputs to the main project model itself. By splitting out the models in this way, a suite of project models was created that enabled a more efficient, but still appropriately detailed, method of LCoE modelling of different project options.

The following main inputs are required for the detailed project model:

- Effective sale price of the electricity (including support mechanisms such as contract for difference)
- Machine yield – annual average generated power at the site
- Machine cost – parts, manufacture, and installation
- Project infrastructure costs (e.g. grid connection, shore plant, etc.)
- Operation and maintenance costs (O&M)
- Margins on each of the above cost contributions
- Financing regime – required project rates of return, and the introduction of debt to the finding mix

Each of these inputs requires a range of modelling and estimation activities in its own right, each with further layers of inputs required to derive suitable results.

3.2.1 INCORPORATING UNCERTAINTY

There has been a strong prevalence to deal with single or 'exact' values in the sector. However, particularly in the early stages of development learning incorporating reasonable uncertainty bounds is essential to understanding the real picture. The inputs to the project model should also include assumed uncertainty ranges represented as probability distributions. This approach helps quantify the risks associated with the inevitable residual uncertainty of projections. Furthermore, this detailed and transparent approach to projections allows underlying assumptions to be readily tested and the sensitivities to be understood. It is possible to ask the question: "What if the maintenance costs are somehow double that?" or "What if we were more ambitious on the scale-up opportunities but with higher uncertainty?" A similar approach may be adopted in quantifying project schedule and budgets generally.

A simple statistical approach to combining uncertainty in inputs assumes those inputs are independent of each other. In some cases this premise may be flawed, however, provided there is a strong awareness of this issue, different explicit scenarios may be developed to manage major combinations of technology options. In this way, uncertainty models in project inputs are not required to represent major combined effects such as machine size, or material choices, etc.

3.2.2 MODELLING MAJOR DESIGN CHANGES

A key objective of the new approach was to effectively compare design options and choices. A particular challenge lies in the combined effect of major design improvements that are not independent. For example, the cost and yield impact of major features such as changes in load limits in the PTO system can only be treated in combination. While metrics may be derived to assist in design choices, such cases must be treated explicitly in combination when modelling LCoE and deriving such metrics. The unforeseen impact on cost outcomes due to the detailed design consequences of changes in machine size or configuration is a particularly strong source of errors in early projections. Sufficiently detailed design and analysis is required for particular choices before such projections may be deemed reliable, and ranges of uncertainty should be conservatively adopted.

3.2.3 IMPACT OF LEARNING

For medium and longer term projection of LCoE, a 'learning model' is required to take current costs and project them forwards as a function of both development time and volume of manufacture. It is common to apply a 'learning rate' combining these effects as a function of volume, and there is remarkable consistency in this approach across a wide variety of technologies – but this is only generally meaningful once substantial volume is achieved. Learning rates are normally applied as percentage of reduction per doubling of installed or deployed capacity. Precedents show that reductions can start as high as 15-20% per doubling in the early stages of the industry but then progressively fall to ~5% per doubling when the technology is well matured.

Due to the fact that learning rates across many sectors can be remarkably similar it is tempting to just use these rates directly to predict the future trajectory. However, to achieve these rates an aggressive target driven R&D and commercialisation programme is required. This is possible for the wave power industry as well but the industry needs to look for where the major opportunities are and design programmes to maximise delivery of them.

Different technology categories within the WEC system must also be treated with different learning potential. For example, it is reasonable to assume that electrical sub-systems using relatively mature components will reduce in cost by just a few % per doubling of installed capacity, while it may be entirely justifiable to assume that the main structures will continue to learn at a much higher rate until costs converge with standard industrial cost/tonne metrics.

In making long term projections for a brand new technology, the assumption of volume itself is the greatest uncertainty – and in policy-making such projections may be self-fulfilling! In developing towards high-volume production, volume learning can only be treated in the context of specific roll-out scenarios and it is therefore helpful to explicitly present projections as such.

It is considered sensible to apply any learning models and specific projections to the individual inputs at as low level a stage as possible, such that they aggregate up through to the LCoE model. As with any estimation process, a granular approach spreads errors allowing them to cancel out while reinforcing the underlying information and understanding. However, a top down approach and comparison with other historical examples at each level should also be made to highlight any anomalies.

3.3 ADDITIONAL MODELS (GENERATING INPUTS TO MAIN PROJECT MODEL)

3.3.1 MACHINE COST MODELS

Machine cost is the predominant factor in the cost of energy equation. This is normal for systems at an early stage of development and for renewables in general. High capital costs incurred up front are offset by low operational costs over the life of the project. PWP had a unique experience in this regard having completed the build, commissioning and operation of six full grid connected machines.

PWP's P1 units originally provided full system costs and the P2 units provided a fully defined benchmark for this technology platform. The move from P1 to P2 gave PWP solid benchmark data and experience for scaling up machines into the future. Based on this experience, the machine cost models were constructed in the following way:

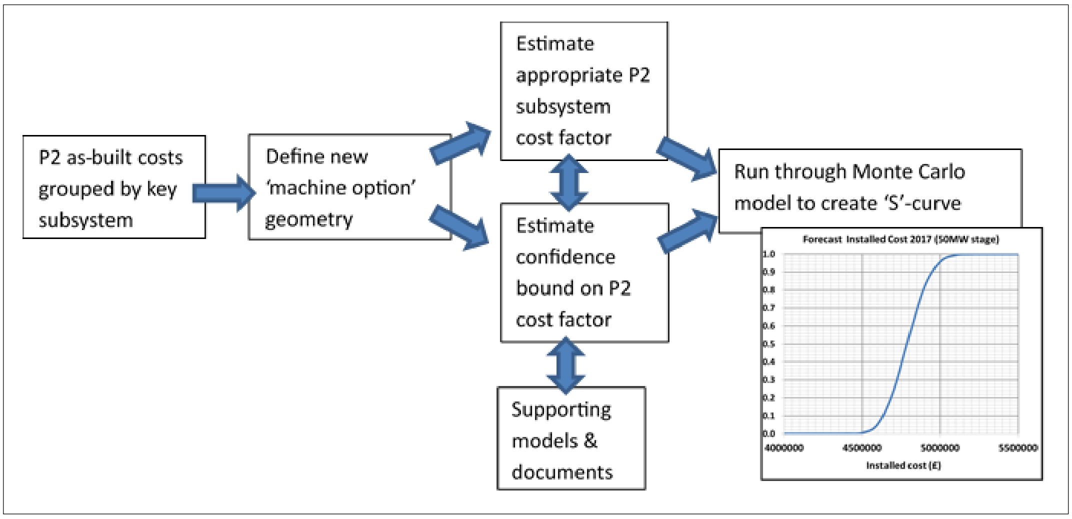


Figure 7– schematic of the system factoring approach to cost estimation of a range of candidate machine geometries

P2 as built costs and cost metrics are factored to generate what PWP called the 'today cost' for other machine configurations. This is essentially the cost that would have been expected for P2 if it had been a different size, or had a different number of joints. The options assumed varied depending on the study being undertaken but PWP were careful not to try to extrapolate data too far, generally the models were used within a scale up range of c. 1.5-1.75:1 at most (comparable to P1 to P2).

Costs for the other variants are generated by applying factors to the lumped sub-system level SPR P2 as built costs. Initial models were on a part by part level but this proved cumbersome and very time consuming so, latterly, it was agreed that costs would be defined on a sub-system level instead (the rationale behind any costs defined still needed to be fully justified however).

3.3.2 LEARNING RATE MODELS

Projected cost reductions to inform the cost of energy projections were derived from detailed analysis at the parts level and peer reviewed and validated through numerous technical due diligence exercises with consultancies and major manufacturers.

The learning & cost reduction model used the same sub-system level models approach. After much debate, trials and assessment of various options, the approach taken to modelling cost reduction was as follows:

- A timeline of machine production rates over the model timespan was set up. This was used to drive the learning rate part of the model as described later.
- 'Machine option' cost and cost uncertainty ranges were read into the sheet from the main cost models.
- Explicit cost reductions were defined for each subsystem line item. These give the reduction expected from the 'Today cost' cost based on as built SPR P2 costs to the projected 'Forecast costs'. These were generally modest or incremental reductions based on experience from the P2 builds, in conjunction with targets from the subsequent development programme.
- The next stage of the forecast is for the first 4 years of subsequent R&D/build/deployment to ~50MW deployed. This is the phase in which the R&D already underway and subsequently planned would be delivering large and reasonably well defined year by year reductions. The reductions at this stage are primarily innovation driven moving to initial volume savings by the end.
- In subsequent years a progress ratio learning model was adopted. However, it was more sophisticated than models commonly used in that each subsystem was assigned its own learning rate based on how conventional that system was and a judgement of learning possible through volume and onward innovation. Four distinct learning rates could be specified. These cover the main classes of system with cost learning rates of 5-10% reduction per doubling of installed capacity used for all of our work at Pelamis.
- The only exceptions to the learning rates applied as above were:
  - Structural steel and painting costs which were assigned a nominal flat 2% per annum reduction based on increasing volume and progressive reduction in material content rather than a higher learning rate.
  - In the models incorporating concrete, main tube elements adopted a different learning approach. Here, a steady reduction from low volume costs to expected high volume asymptotes was assumed.

A Monte Carlo loop is then set up around these inputs to generate 'S-curves' of cost which can then be interrogated and extracted in to the project mode itself. The expected and (typically) 5% and 95% confidence bounds from this were then read off for use in the Project Model input tab.

Example outputs from the machine cost learning model are shown below in Figure 8.

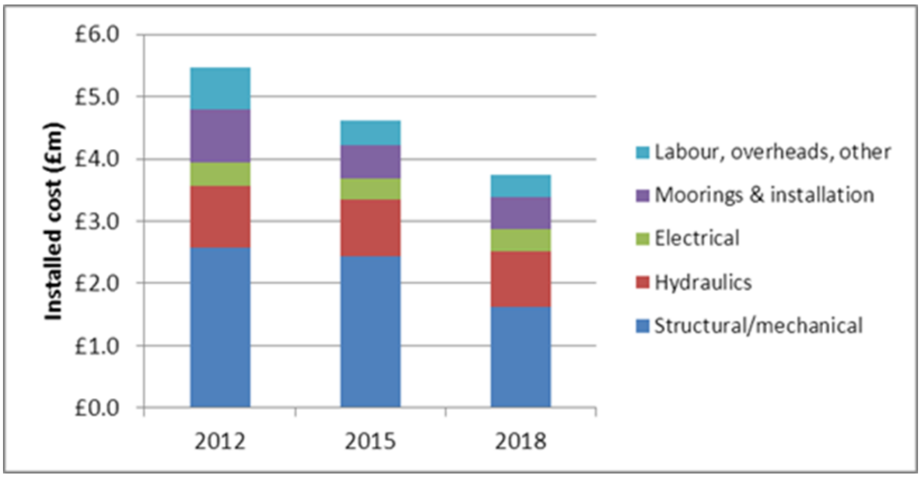


Figure 8 – example cost break down showing cost reductions expected over six years.

3.3.3 OPEX & AVAILABILITY MODELS

Another primary factor in the cost of energy equation is the cost of Operations and Maintenance ('O&M') and the impact of the resulting machine 'availability' on net energy yield. PWP put a large amount of effort into modelling this since with confidence increasing in the Capex and initial yield forecasts, reliability, availability and associated O&M 'Opex' costs were at the time becoming the single biggest source of remaining uncertainty in the LCoE equation.

Two main approaches were used to investigate and characterise the Opex and availability for initial farms and longer term projects.

- A main subsystem level reliability and O&M / repair model – this was set up on a *'system-effectiveness'* basis as described below.
- A simple fixed and variable cost model assuming a realistic number of interventions/repairs informed from the above model.

The availability of the machines and the cost of operating and maintaining them was estimated using a project operations model. Inputs into this model were informed by a system level FMEA and assumed probability of failure of components and systems, along with the costs to retrieve, repair, and install machines, and seasonal variability of both revenue and weather windows. This is a *'system-effectiveness'* approach where the *'cost of availability'* can be assessed and an optimum struck in the O&M strategy. Initial versions of this model were created to investigate what level of reliability and what intervention capability/frequency would be required in a commercial system.

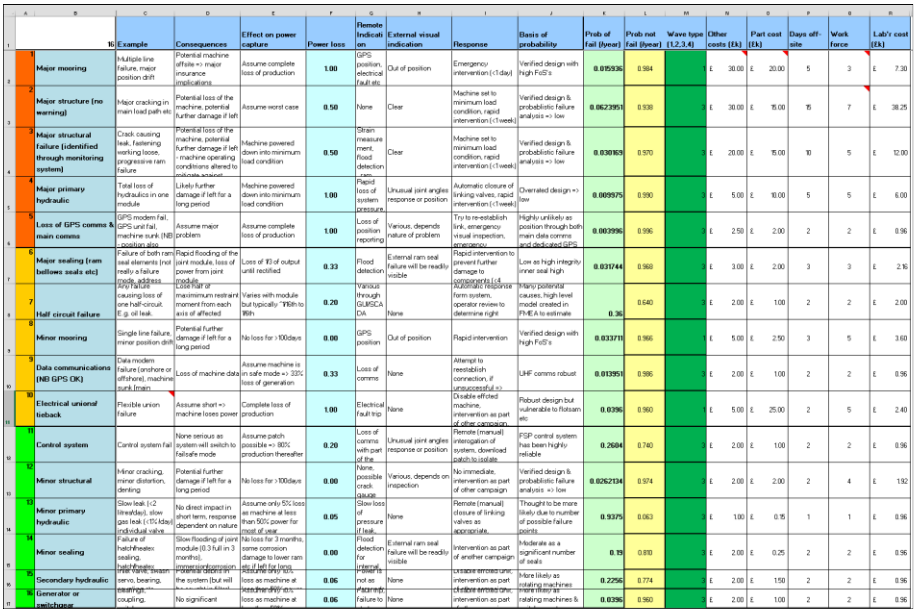
The main uncertainty in these models was the actual failure rates of the components used. This uncertainty reduced considerably through the P2 programme. Throughout the development and operational programme, the model was continuously modified and extended to take in ever more realistic estimations of reliability and to include demonstrated capabilities in intervention and repair. The model increasingly became invaluable to highlight the key areas where reliability had to be demonstrated and improved and was therefore used as a valuable input to the development and demonstration programme itself.

To reduce uncertainty, where practicable, the robustness and reliability of individual components had been tested with targeted functional tests (for example: penetration testing on bellows seals; wear testing of bearings under partial failure / water ingress), and with accelerated cycle testing (for example: control valves, hoses, and fittings were under on-going population cycle tests, hydraulic cylinders, bellows seals; and cable transits). PWP completed various functional and life cycle testing programmes in house and with it suppliers. However, more could have been done here and onward development was focused on more rigorous plans to advance this aspect in parallel with machine testing for the next stage of development.

At the time of PWP administration, the O&M model included a total of 16 major fault classifications: five 'RED' major faults where the integrity or safety of the machine is at risk, five 'AMBER' or intermediate faults where there is a major impact on generation or potential escalation in terms of safety or integrity, and six 'GREEN' or minor faults which only have an impact on generation/yield. Many more cases could have been modelled but it was felt that this was the right resolution for the stage of development and Quoceant would recommend this to other WEC developers. In addition to the fault types, two scheduled maintenance tasks were defined and incorporated in the analysis.

Each of the fault types was ascribed a range of numerical impacts/probabilities in terms of impact on generation, likelihood, time/cost to repair. This allows a Monte Carlo s model to be created around these figures and realistic scenarios of machine interventions, maintenance times and availability generated.

The O&M model included sophisticated decision-making models on intervention, retrieval and reinstallation, and took account of real performance projection data to estimate impact in yield of the faults and downtime. Later versions of the model also included a sophisticated optimiser tool that allowed the most economic options and decisions to be taken. As such, once the reliability and yield impact data had been validated the model would have formed the basis of a valuable operational tool to help with planning and optimising the availability and O&M of real farms had they been built.



	16	Example	Consequences	Effect on power capture	Power loss	Remote Indication	External visual indication	Response	Basis of probability	Prob of fail (/year)	Prob not fail (/year)	Wave type (1,2,3,4)	Other costs (£k)	Part cost (£k)	Days off-site	Work force	Lab'r cost (£k)
1	**Major mooring**	Multiple line failure, major position drift	Potential machine offsite => major insurance implications	Assume complete loss of production	**1.00**	GPS position, electrical fault etc	Out of position	Emergency intervention (<1 day)	Verified design with high FoS's	**0.015936**	0.984	1	£ 30.00	£ 20.00	5	3	£ 7.30
2	**Major structure (no warning)**	Major cracking in main load path etc	Potential loss of the machine, potential further damage if left	Assume worst case	**0.50**	None	Clear	Machine set to minimum load condition, rapid intervention (<1 week)	Verified design & probablistic failure analysis => low	**0.0623951**	0.938	3	£ 30.00	£ 15.00	15	7	£ 38.25
3	**Major structural failure (identified through monitoring system)**	Crack causing leak, fastening working loose, progressive ram failure	Potential loss of the machine, potential further damage if left - machine operating conditrions altered to mitigate against	Machine powered down into minimum load condition	**0.50**	Strain measure ment, flood detection, ram	Clear	Machine set to minimum load condition, rapid intervention (<1 week)	Verified design & probablistic failure analysis => low	**0.030169**	0.970	3	£ 20.00	£ 15.00	10	5	£ 12.00
4	**Major primary hydraulic**	Total loss of hydraulics in one module	Likely further damage if left for a long period	Machine powered down into minimum load condition	**1.00**	Rapid loss of system pressure,	Unusual joint angles response or position	Automatic closure of linking valves, rapid intervention (<1 week)	Overrated design => low	**0.009975**	0.990	3	£ 5.00	£ 10.00	5	5	£ 6.00
5	**Loss of GPS comms & main comms**	GPS modem fail, GPS unit fail, machine sunk (NB - position also	Assume major problem	Assume complete loss of production	**1.00**	Loss of position reporting	Various, depends nature of problem	Try to re-establish link, emergency visual inspection, emergency	Highly unlikely as position through both main data comms and dedicated GPS	**0.003996**	0.996	3	£ 2.50	£ 2.00	2	2	£ 0.96
6	**Major sealing (ram bellows seals etc)**	Failure of both ram seal elements (not really a failure mode, address	Rapid flooding of the joint module, loss of power from joint module	Loss of 1/3 of output until rectified	**0.33**	Flood detection	External ram seal failure will be readily visible	Rapid intervention to prevent further damage to components (<4	Low as high integrity inner seal high	**0.031744**	0.968	3	£ 3.00	£ 2.00	3	3	£ 2.16
7	**Half circuit failure**	Any failure causing loss of one half-circuit. E.g. oil leak.	Lose half of maximimum restraint moment from each axis of affected	Varies with module but typically ~1/16th to 1/6th	**0.20**	Various through GUI/SCADA	None	Automatic response form system, operator review to determine right	Many potential causes, high level model created in FMEA to estimate	**0.36**	0.640	3	£ 2.00	£ 1.00	2	2	£ 2.00
8	**Minor mooring**	Single line failure, minor position drift	Potential further damage if left for a long period	No loss for >100days	**0.00**	GPS position	Out of position	Rapid intervention	Verified design with high FoS's	**0.033711**	0.966	1	£ 5.00	£ 2.50	3	5	£ 3.60
9	**Data communications (NB GPS OK)**	Data modem failure (onshore or offshore), machine sunk (main	Loss of machine data	Assume machine is in safe mode => 33% loss of generation	**0.33**	Loss of comms	None	Attempt to reestablish connection, if unsuccessful =>	UHF comms robust	**0.013951**	0.986	3	£ 2.00	£ 1.00	2	2	£ 0.96
10	**Electrical unional tieback**	Flexible union failure	Assume short => machine loses power	Complete loss of production	**1.00**	Electrical fault trip	None	Disable effcted machine, intervention as part of other campaign,	Robust design but vulnerable to flotsam etc	**0.0396**	0.960	1	£ 5.00	£ 25.00	2	5	£ 2.40
11	**Control system**	Control system fail	None serious as system will switch to failsafe mode	Assume patch possible => 80% production thereafter	**0.20**	Loss of comms with part of the	Unusual joint angles response or position	Remote (manual) interogation of system, download patch to isolate	FSP control system has been highly reliable	**0.2604**	0.740	3	£ 2.00	£ 1.00	2	2	£ 0.96
12	**Minor structural**	Minor cracking, minor distortion, denting	Potential further damage if left for a long period	No loss for >100days	**0.00**	None, possible crack gauge	Various, depends on inspection	No immediate, intervention as part of other campaign	Verified design & probablistic failure analysis => low	**0.0262134**	0.974	3	£ 2.00	£ 2.00	2	4	£ 1.92
13	**Minor primary hydraulic**	Slow leak (<2 litres/day), slow gas leak (<1%/day) individual valve	No direct impact in short term, response dependent on nature	Assume only 5% loss as machine at less than 50% power for most of year	**0.05**	Slow loss of pressure if leak,	None	Remote (manual) closure of linking valves as appropriate.	Thought to be more likely due to number of possible failure points	**0.9375**	0.063	3	£ 1.00	£ 0.15	1	1	£ 0.96
14	**Minor sealing**	Failure of hatch/heatex sealing, hatch/heatex	Slow flooding of joint module (0.3 full in 3 months), immersion/corrosion	No loss for 3 months, some corrosion damage to lower ram etc if left for long	**0.00**	Flood detection for internal,	External ram seal failure will be readily visible	Intervention as part of another campaign	Moderate as a significant number of seals	**0.19**	0.810	3	£ 2.00	£ 0.25	2	2	£ 0.96
15	**Secondary hydraulic**	Inlet valve, swash servo, bearing,	Potential debris in the system (but will	Assume only 10% loss as machine at	**0.06**	Power is not as	None	Disable effcted unit, intervention as part	More likely as rotating machines	**0.2256**	0.774	3	£ 2.00	£ 1.50	2	2	£ 0.96
16	**Generator or switchgear**	coupling,	No significant	loss as machine at	**0.06**	Fault trip, failure to	None	intervention as part	More likely as rotating machines &	**0.0396**	0.960	3	£ 2.00	£ 1.00	2	2	£ 0.96

Figure 9 – Screen grab from the O&M model

In addition to the detailed system-effectiveness model and tools described above PWP also estimated O&M costs from a 'top-down' perspective assuming a specific model of the fixed and variable costs of resources and facilities required to service a given project. This approach was particularly useful for smaller projects where the system-effectiveness model can be optimistic due to difficulty representing vessel market issues that can dominate with only few machines to support, and the need to have minimum staffing levels to cover key functions and skills needed as well as ensuring health and safety requirements are met. For a small farm with a dedicated vessel, this model provided a good order of magnitude 'cost backstop' for economic modelling as the fixed costs assumed could support much lower reliability than expected at little marginal cost. It also provided a simple order of magnitude check for the more complex model, clearly demonstrated the rapid reduction in annual machine O&M as fixed costs were shared across multiple machines and allowed the key Pelamis O&M principles and characteristics to be more easily communicated to investors and customers ahead of more thorough Due Diligence.

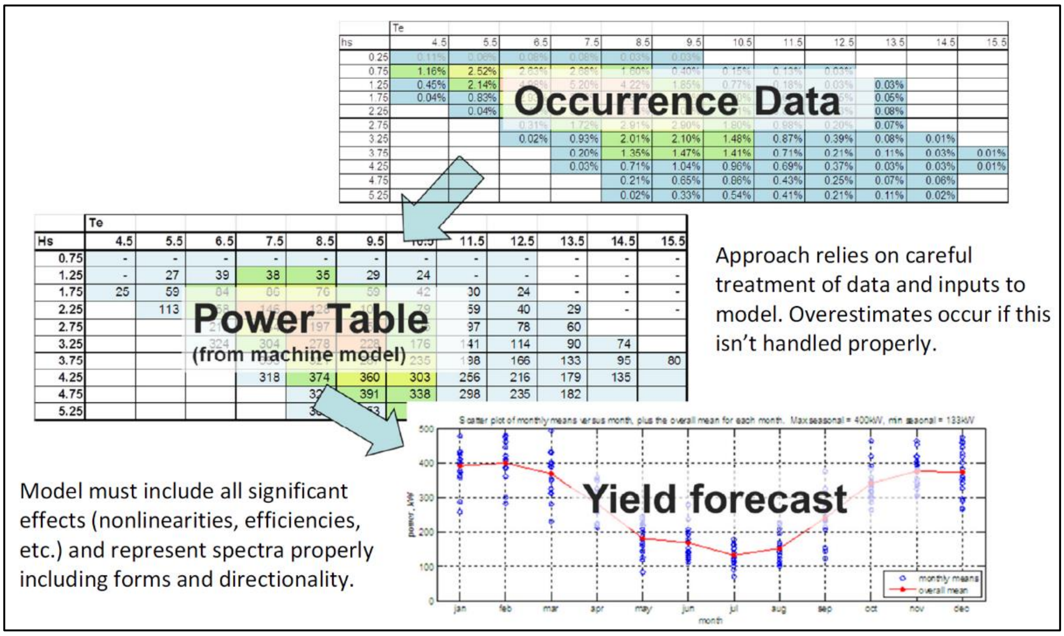
O&M cost validation

PWP's O&M model and assumptions had been peer reviewed in detail on many occasions by various consultants. Vattenfall in particular reviewed O&M costs and availability in detail. They focused on independent validation of availability and O&M costs using their own approach – they created an independent 'Markov chain' model as verification of PWPs Monte Carlo numerical methods. The two models agreed to an acceptable level of accuracy and Vattenfall's conclusion was that the results were sound.

3.3.4 YIELD

Annual energy 'yield' from the machine is another primary factor in the cost of energy equation. Yield is perhaps the biggest area where optimism bias is present in early wave energy LCoE forecasts and there is no easy shortcut round this. Summarised below is the eventual process adopted at PWP in this key area.

The annual average energy production is estimated for a given site using historical wave resource records for the site and simulations of the machine across the full range of sea conditions.



Approach relies on careful treatment of data and inputs to model. Overestimates occur if this isn't handled properly.

Model must include all significant effects (nonlinearities, efficiencies, etc.) and represent spectra properly including forms and directionality.

Figure 10 – schematic of process to create yield forecast from resource and machine performance data. In practice the process is much more complex.

The first essential step in yield projection is to understand the wave regime in which the machine will operate. PWP used as a minimum, wave resource data that was derived from 10 years of 'hindcast' meteorological records and this was, where possible, calibrated using one or more years of directional wave-buoy measurements from the site.

However, 10 years' worth of 30-minute spectral data is a large data set to work with and a more time and cost effective methodology for accurate yield projection using a reduced data set needed to be found and validated. The approach PWP developed was to use the concept of a *'mean measured spectra'* within each Hs-Te cell. The directional spectral for all occurrences in each Hs-Te cell were averaged to generate a *'mean measured spectrum'* for that cell which could be used as a reliable proxy for the hundreds, perhaps thousands, of individual records.

This methodology was carefully validated using PELs (PWP's in-house simulation tools) to confirm that is was a good proxy. As so often in wave energy the mean measured spectrum results gave almost universally lower yield forecast per cell than using a standard form with either the mid-point Hs & Te for each cell or more robustly an average Hs & Te alone from the cell data. Mean measured approach generally gave forecasts as much as 10-20% less than simple estimates making it a very material effect for economic forecasts.

The PWP 'PELs' simulation software used to derive machine yield was verified using tank tests, existing industrial software, and, most importantly, direct comparisons with operational machines in real waves. The simulation represented the cutting edge of numerical modelling of wave energy conversion and included non-linear hydrodynamics & kinematics, directional wave spectra, detailed power take-off models, and finite element mooring models running fully integrated in the time-domain. It was for all intents and purposes a validated 'virtual machine' for the size and rating of machines developed.

The PELs simulation tools were used for a number of purposes over a number of years the prime focus was using it as one of the main design tools for the machines. The same capability was of course vital for forecasting the yield of the machine on specific project sites and PWP had been marketing this capability for a number of years to prospective developers. Increasingly the simulation was being used to inform the technology development path going forwards.

Figure 11 shows the measured power from an operational P2 machine over a number of days plotted alongside the corresponding simulation of that machine using the wave-buoy measurements for each 30minute period as input. The agreement is within a few percent on average. Gaps in the data are when wave buoy data was bad or missing or when machine controls were being changed to manage response. Agreement is excellent and on average across many thousands of hours was within 5-10%. This data is particularly interesting as through the morning of the 7th November the machine was running at 200-275kW 30 minute average in steep short period seas. This shows agreement from the non-linear PELs programme extended well into this higher power, non-linear region.

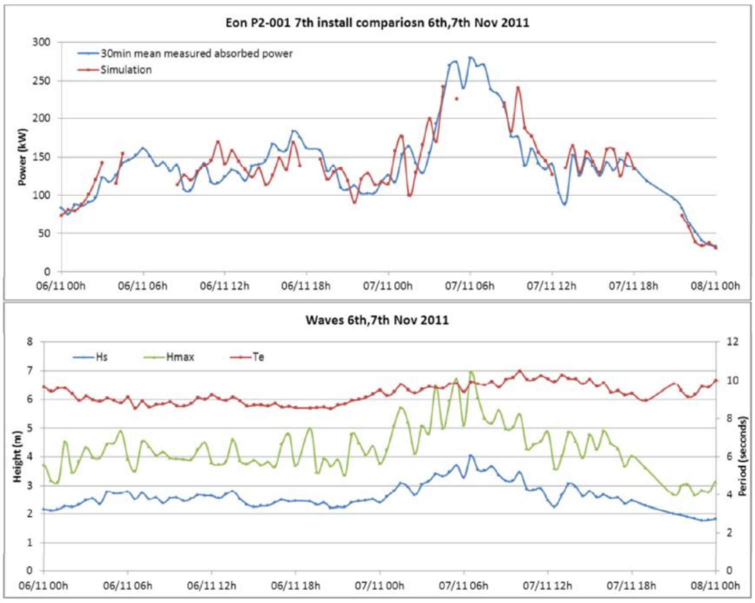


Figure 11 – above shows similar data for P2-001 operating at EMEC in 2011, this time with re attendant wave buoy data plotted below.

Modelling yield uncertainty

A key part and perhaps dominant of uncertainty in LCoE is the confidence with which yield can be predicted. The validation of the simulation with tanks and real at sea data of course removed a huge level of uncertainty with basic yield forecasts for the Pelamis system. However, considerable uncertainty remains regarding a number of key factors including the projected increase in yield through both changes to machine geometry and PTO/control advancements. PWP developed a methodology to combine the residual uncertainties in an objective manner to create a compound uncertainty model and distribution for inclusion the project model. The best fit distribution for our data turned out to be a lognormal distribution.

What was very interesting and informative was the progressive reduction in yield projections as projections were refined and uncertainty was reduced. Early projections based on linear hydrodynamics, simple idealized PTO and control algorithms that are unachievable in real engineered systems were factors above what was actually deliverable from real machines, in real seas. This is a problem that has materially hindered progress in the sector as new, early stage ideas invariably look much more attractive on paper than real systems in the tank and then in the sea.

Yield projections for future machines

Improving machine yield was a major input to the cost of energy equation. PWP had identified and researched many and varied options for improving machine yield going forwards, including:

- Improvements on a given platform (e.g. improving and optimising controls, improving efficiencies, optimising heading etc.)
- Improving the platform itself (e.g. Improving the primary PTO system to enhance the system's ability to apply/control complex forces and moment on the joint, increasing the tube diameter, length and number of joints, or optimising the tube cross section and distribution of volume.

A mixture of these two approaches was used to derive a yield projection for the Pelamis machines as they went through incremental product cycles into the future. The yield profile assumed in the cost-of-energy trajectory is shown in Figure 12 below. In this case the band indicates variation depending on the site wave resource intensity. The upper values are for an aggressive site such as the West Coast of Scotland, the lower levels correspond to a more moderate resource such as Orkney or Portugal.

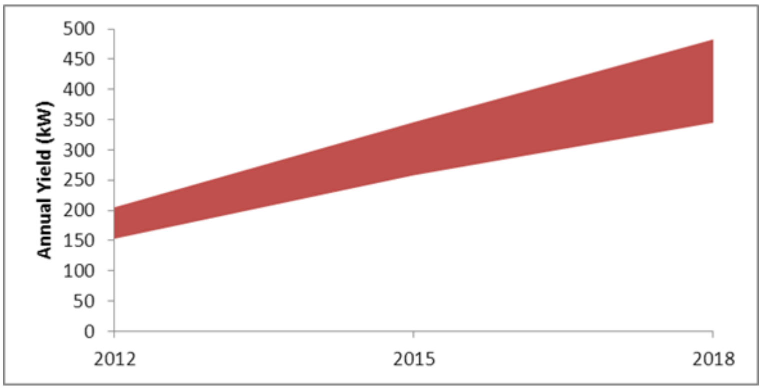


Figure 12 – example of yield improvement projections from modelling work

Yield validation

In summary, validation of PWP simulation tools for P1 & P2 machines was completed for wave heights up to 5.0m Hs, and while this is not the full operating regime it covers the high occurrence sea states most important for predicting annual energy yield. In addition to completion and full peer review of direct validation of our models with full scale and tank data, PWP also completed a number of other direct validation exercises against industry standard codes such as Atkins AQWA and Orcina Orcaflex.

As well as solid validation of basic performance models, various initial implementations of higher power 'MIMO' control algorithms had been demonstrated to increase expected annual average power by some 40-50% in the wave tank, and preliminary demonstrations at sea with P2 led to an impressive ~17% increase in expected annual average output, with some 37% increase for wave periods > 8seconds (Figure 13 below). These gains from control were extremely important as they demonstrated a strong move in yield back in a positive direction after the many years of erosion of estimates due to the various real-world effects. However, only the very first demonstrations were completed (~100hours) prior to PWP entering administration so the full potential of this avenue or research was of course never realised or demonstrated.

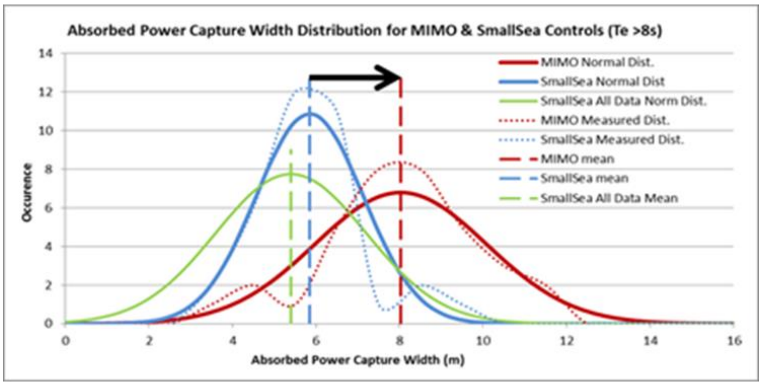


Figure 13 – impact of 'MIMO' controls on P2 power absorption

3.4 DISCUSSION & RECOMMENDATIONS

Quoceant believe that the set of models described above were a sound and robust set of tools for guiding onwards development of the Pelamis system. Building from the initial work, and when FOAK costs are reasonably well defined, constructing and characterising a set of detailed models such as these is critical to understanding the real CoE drivers for a given system and site. They create a focus and a language for discussion and presenting options and for assessing residual uncertainty in a format and 'taxonomy' that utility partners and investors were familiar with.

Used correctly they were very informative but adopting such a detailed approach has its pitfalls as the level of detail can result in a false level of confidence and mask major residual uncertainties and errors. Any model is only as good as its inputs, and 'GIGO' ('Garbage-In-Garbage-Out') applies no matter how robust the LCoE model. This said, with appropriate review and validation, once believable starting points have been ascertained, the level of detail provided in these models is required to enable a well-informed dialogue about key choices and options.

A key learning step was that progress ratios individually applied and weighted to each key input. This is vital as progress in many areas is driven by different things. Some aspects are dominated by innovation and can be pursued through targeted R&D, others come naturally with increasing volume of manufacture, still others are linked primarily to economies of scale at a project and regional level.

Attempting to separate out the individual contributions allows more objective demonstration of key points regarding the role of R&D, sub-scale demonstrations and then industrialisation with regard to initial and onward CoE estimates compared to experience with other renewable and energy technologies. The modelling completed at PWP was a solid first pass at stripping out and independently treating these various contributions. However, if the modelling process was started again now, an even more explicit approach to doing so would be employed.

In retrospect the approach of explicitly modelling the first 4 years of development then moving to learning rates was good in principle, but in practice it would be even better to try to separate out innovation led and volume driven cost reduction entirely. No such process would be perfect but with some more work on general volume reduction metrics an even better process could be set up. In addition, a move to incorporate product lifecycles would make it even more credible and believable. It is not realistic to introduce and capitalize on major innovations every year, rather each product would have a lifecycle of say 3 years with a few refinements along the way.

Including, then debating and agreeing uncertainty bands in the cost model is critical to avoid either optimistic (usually in the case of the developer) or pessimistic (usually in the case of a buyer) tendencies on cost & yield being compounded and giving inaccurate results. PWP put much effort into this in the models described in this section, each uncertainty value/range was discussed and agreed with stakeholders. When new validation results were generated/secured, the relevant uncertainty bounds were reassessed accordingly.

In addition to looking at learning effects, the Machine Installed Capex model provided a very solid basic methodology for objectively comparing a number of machine options. Adoption of transparent factoring approach to create 'today' costs for various machine configurations is a good one, but limits of extrapolation needs to carefully considered. The models were used, reviewed and refined over a number of years and provided a sound basis for tracking validation of inputs using the P2 machines, and collection of wave and other data for specific sites. As mentioned above, they became very useful for justifying technical choices and setting research goals for the forthcoming steps towards commercial demonstration.

4. ETI WEC MODELS

4.1 OVERVIEW & APPROACH

In 2012 PWP won the Energy Technologies Institute Wave Energy Converter (‘ETI WEC’) tender process to conduct a project to identify, research and detail options to deliver more rapid reduction in wave energy CoE, with the objective to meet the ETI’s own roadmap targets for 2020 and 2050.

The basis for the project was the detailed LCoE modelling tools already developed but, with the number and scope of options being considered becoming much broader and ‘revolutionary’ in nature rather than the narrower ‘evolutionary’ options being advanced for utility partners. Once this process had commenced, it rapidly became clear that a higher level model more suited to efficient preliminary assessment of the relative impact of a wider range of configurations was required.

The project set out to conduct a ‘root and branch’ review of opportunities for accelerated LCoE reduction and convergence with mature renewable technologies. It looks at all aspects of the LCoE equation across yield and cost as summarised in Figure 14 below.

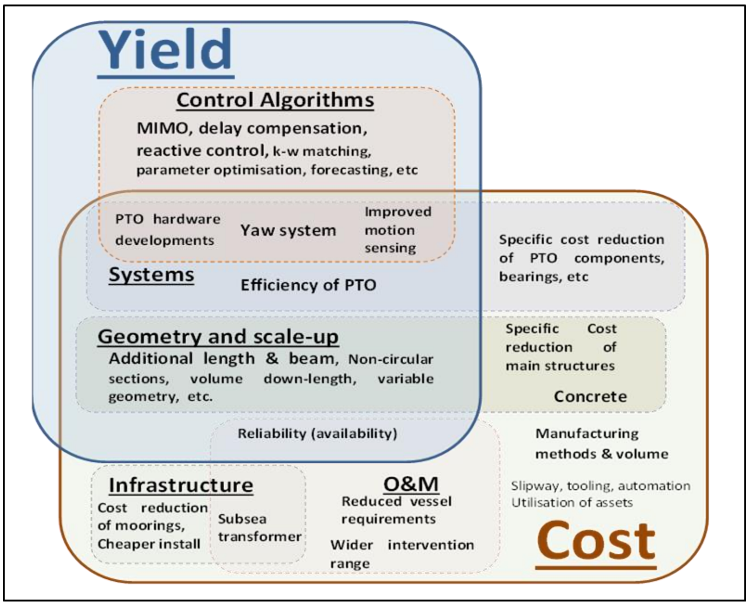


Figure 14 – Summary of key LCoE factors included in ETI WEC study

The ETI WEC project considered a vast array of options, narrowed down to approximately 60 different innovations or adaptations for accelerating LCoE reduction ranging from different sizes of machine, different numbers and configurations of joints, alternative structural materials, improved PTO, revised mooring connections etc. In order to keep analysis ‘tractable’, these were assessed, down selected, then grouped into a more modest number of ‘configurations’ for LCoE assessment. Grouping was subjective but designed to ensure that all necessary innovations for a specific function (be it structural/bearings/PTO etc) were included. The process can be summarised as follows:

- Establish a baseline P2e design and LCoE model to enable innovation impact assessment.
- Rank innovation options in terms of anticipated impact on LCoE, and down-select to define ranked set of innovations with highest impact.
- Group and embody the priority innovations in a reduced number of ‘P2e+ machine configurations’ to allow more thorough LCoE impact assessment of a sensible number of candidate options.

- Consider capex of major adaptations at a parts level again (as subsystem grouping approach becomes unreliable for major changes).
- Consider impacts in yield using generalized modelling in PELs working within carefully set engineering constraints consistent with the range of validation available.
- Construct a new simplified LCoE model based on lumped-parameter representations of balance of project and financing costs in conjunction with Capex and Yield estimated from the above. The new model reverted to the familiar *NPV(costs)/NPV(yield)* approach rather than the full financial model.
- Use the above model to create families of curves for LCoE for the chosen configurations, and further variations thereof.
- Carry out benchmarking runs using the old full models to show that results were self-consistent and within 5-10% of the full model predictions.
- Create scenarios where major innovations are introduced in stages following appropriate R&D and prototyping to produce example accelerated LCoE reduction curves.
- Complete a 'cost to commercialise' or 'cost to converge' analysis to determine the impact of the innovation on the overall cost of deployment.
- Consider next steps and repeat the loop as required.

The assumed deployment and cost profiles for the simplified LCoE modelling tools are shown below.

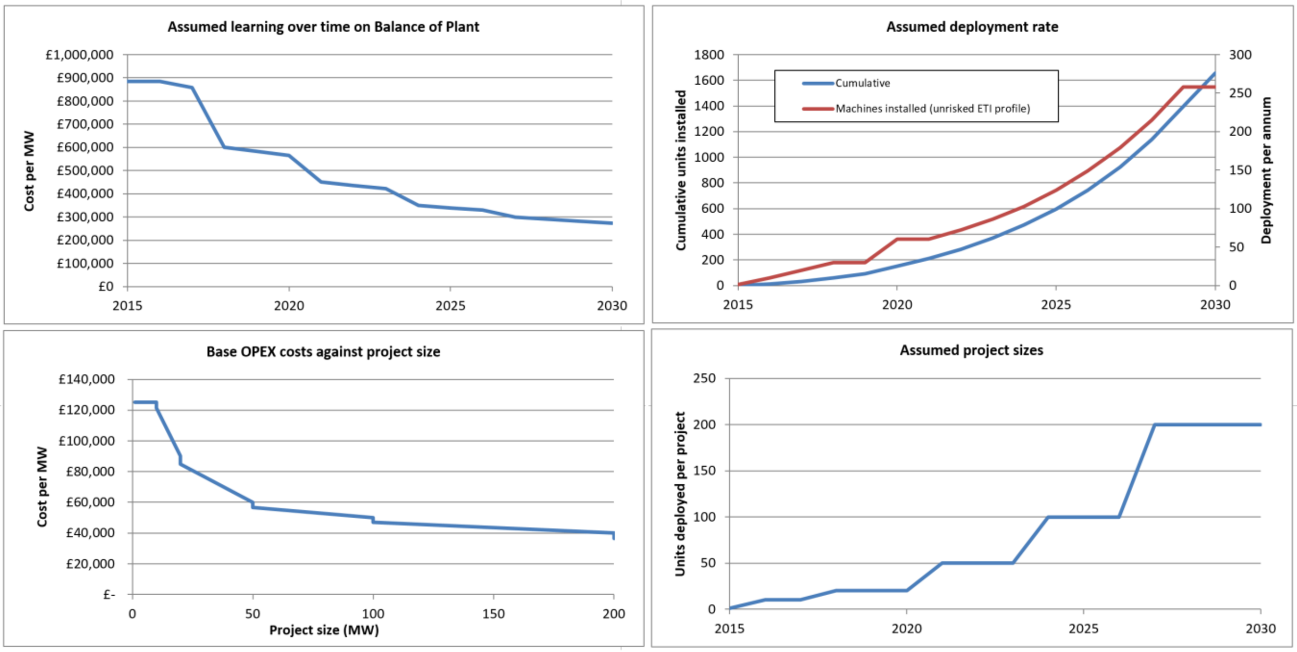


Figure 15 – Assumed deployment and cost profiles for the simplified LCoE modelling tools:

(top right) deployment profile assumed for the ETI WEC analysis with major deployments starting in 2020 and annual installed capacity (red) rising to 250MW/yr and cumulative installed capacity (blue) of ~1.6GW by 2030;

(bottom right) assumed array size through this process with small 10-20MW test arrays to 2020 increasing to 100-200MW scale by 2030 (c.f. Round 1 & 2 UK offshore wind);

(top left) balance of plant costs through the same period moving from detailed estimates for 10MW arrays at ~£1m/MW down to an asymptote of ~£300k/MW which PWP believed was similar to prevailing offshore wind costs for similar scope;

(bottom left) machine and project O&M costs falling from explicit fixed/variable cost model for 10 MW arrays to ~£40k/MW/annum for large arrays from the main O&M model.

4.2 OVERVIEW OF KEY RESULTS AND INSIGHTS

The models developed for the ETI project utilised the detailed cost build up and then reduction tools and methods developed for the full project models with uncertainty values assigned. Yield models were again just as thorough as for the full model case, but again only the expected value was used in this analysis rather than the full distribution. The only real simplification with these models compared to the more comprehensive model set was therefore the simple discounted cashflow model for LCoE and the removal of the Monte Carlo uncertainty elements. This modest simplification, however, allowed many more cases and scenarios to be readily analysed and compared.

The models were set up and benchmarked against the more complex tools. Third party review was involved throughout and a wide range of sector stakeholders including investors, utility partners, the ETI, the Carbon Trust and the Crown Estate involved in a stakeholder review group. Agreement was good throughout, generally the simple tools slightly underestimate LCoE by ~5-10% due to lumped Capex and Opex assumptions and various minor omissions or simplifications involved. However, this was deemed sufficient for the purposes of properly examining the impact of the various innovations on LCoE.

With the tools in place and validated to an acceptable level they became extremely useful and efficient for comparative cost-benefit analysis. The simple and transparent assumptions were easy to explain and justify and the approach allowed a large number of scenarios to be quickly run compared to what would have been a very laborious and unnecessarily complex process with the full models. Full impact reports were produced along with further analysis leading to a prioritised ‘Phase 2’ proposal to deliver the major innovations identified.

Figure 16 presents a simplified graphic of the main outputs and programme from the work. The LCoE reduction curve follows an aggressive stepped-sloped curve as both volume and innovation aspects are incorporated. It was assumed that the annotated major innovations were incorporated in three main stages, probably coinciding to major ‘product life-cycles’ as had been seen in other energy technologies. However, within the analysis a much larger number of more minor innovations and refinement are assumed to be incorporated. In particular, advancements in control algorithms was ongoing with an assumed 2.6% performance improvement per annum designed to give a realistic 50% increase in yield over 15 years of development. In practice, this may have been conservative, in particular with regard to timing. As with all development work like this the major gains come quickly at the start of the programme and improvements becoming progressively smaller and harder to deliver later on. As such PWP believed that the LCoE trajectory presented was probably pessimistic in this regard. However, it was decided that keeping it to a flat profile was appropriate and provided a level of ‘cover’ for other things that may not deliver etc.

Part of the process was to try to set up realistic and defensible uncertainty bounds on the work. These are shown dotted in Figure 16 and were based on running the LCoE analysis using explicit assessment of uncertainty for major changes in conjunction with high and low bounds in the old analysis for other areas. The resulting band is broad but probably not unrealistic given the state of development and demonstration of the technology and the scale of innovation being undertaken.

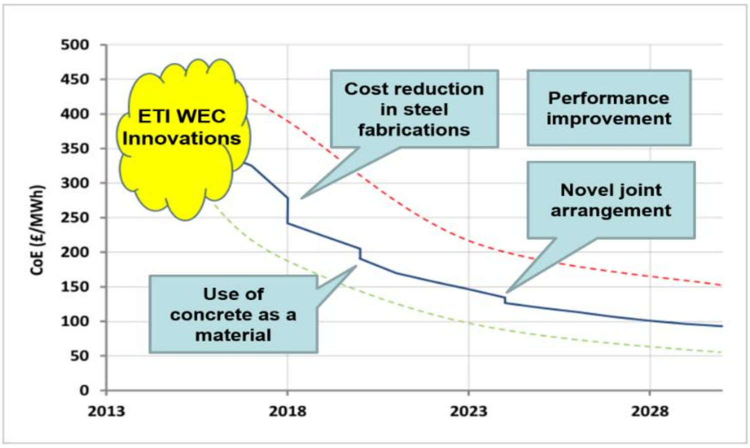


Figure 16 – summary of ETI WEC LCoE trajectory with key features and estimated uncertainty bounds

As with any development programme it is very important to keep relating the outcomes to the original objectives of the programme. Figure 17 overlays the forecast LCoE curve as described above on the original target profile in the ETI bid. As can be seen, aside from the lag at the start while key R&D work would be completed, the projections from the analysis and designs work in the ETI WEC work came close to delivering the intended impact. With a faster control algorithm learning rate and sufficient budget for aggressive parallel R&D on the other aspects it is believed that PWP could have actually hit or bettered the target the curve.

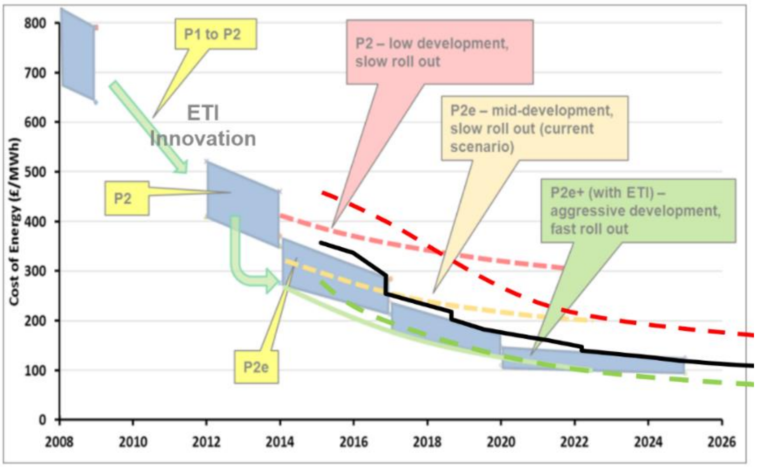


Figure 17 – projected profile overlaid on project target profile indicating original objectives were substantially met

4.3 COST TO CONVERGE ANALYSIS

While the LCoE curves themselves are interesting, and the trajectory looked promising, even this is only part of story. Just like all preceding energy technologies one way or another the market must support commercialisation or convergence process and thereafter the range of costs that employed technologies have in the long term. Within the old nationalised structure this was somewhat opaque with the mix of technologies just feeding in to arrive at an aggregate average cost of power borne by the consumer. Since liberalisation of the markets individual power costs have generally become more visible and specific market instruments been devised and implemented to encourage the desired portfolio (such as the Renewables Obligation and now Contracts for Difference and the new Capacity Market in the UK). It was becoming increasingly clear with the introduction of the Levy Control Framework and the push for earlier and more direct competition that wave and tidal energy was in a difficult position with expectation on the time and cost of converging with other more mature low carbon generation becoming more and more unrealistic.

PWP decided to estimate the cost to converge for various Pelamis configurations and development programmes created in an initial attempt to illustrate what was required for the Pelamis system, set in the context of costs and progress in other sectors, and clearly demonstrate the value of aggressive innovation now (rather than just leaping to volume deployment with an early stage technology). The objective was to show that the right mix of innovation and deployment would maximise the rate of progress, minimise the cumulative cost to the consumer and maximise attractiveness of the sector to investors. This really was created and presented as an initial analysis and PWP somewhat regret not taking it further as it may have influenced thinking and public/private investor appetite for the system and sector.

The first pass analysis used was quite simple and was based on the Net Present Value of the aggregate cost of power to the consumer for various scenarios. The graphs below show summary LCoE profiles and cumulative market cost results for the base and accelerated LCoE scenarios presented previously. The right graph shows that even the base scenario results in a cumulative market support of £10-12bn (NPV today) to bring costs down to £100/MWh with several GW deployed. This, while being a considerable cost of course, is actually very small in the context of the total costs of power to the consumer, the Levy Control Framework for Renewables (or indeed the CfD for new nuclear to deliver a similar supply level). However, the more exciting result is the high innovation case indicates NPV of cost of around ‘only’ £2bn with ~£1.5GW installed to converge to £100/MWh. If achieved, this would have been a stunning result.

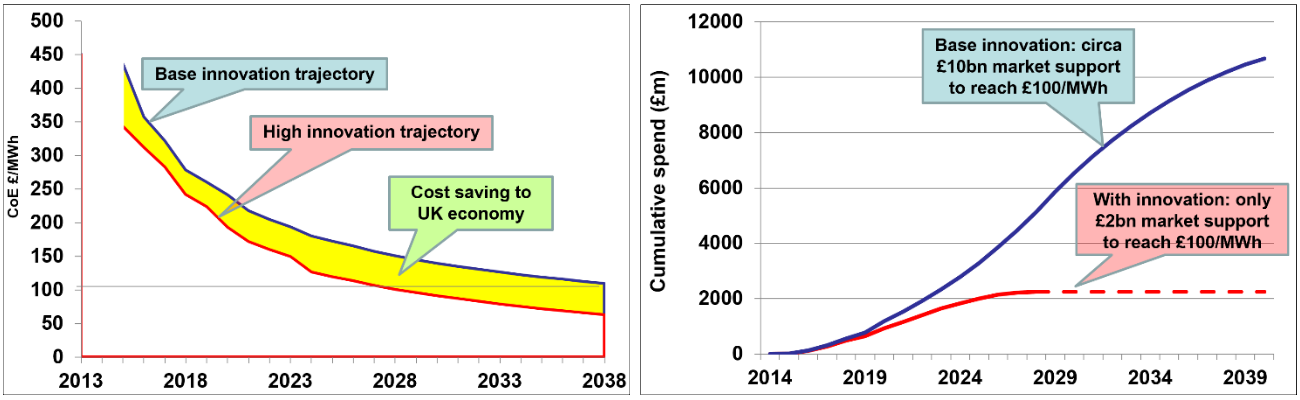


Figure 18 – (left) comparison of pre-ETI WEC base scenario and higher innovation trajectory post ETI estimates, showing much earlier cost convergence and much lower required subsidy total. (right) Comparison of ‘cost to converge’ on £100/MWh for the two cases indicating the substantial value of and return on investment in accelerated innovation for an early stage technology such as this. It is worth noting that even the base scenario indicates a cost to commercialise substantially less than preceding renewable technologies.

While this was very exciting, caution is still required. What the work did indicate was that this is an area that should be further studied in more detail for wave energy, and indeed for many other emerging or maturing technologies. It highlights the need to carefully mix innovation and deployment in the optimum way. Too much innovation and too little deployment and revenues along the way for the promise of big markets in the future stifles investor appetite for R&D, too fast a race to deploy renders innovation too risky to be incorporated leading to volume deployment of immature technology at increased cost. Looking back, it is likely that the costs to converge in onshore and now offshore wind and solar PV have been many hundreds of billions of pounds. While progress was rapid and convergence fast by conventional standards, more could probably have been done to reduce the cumulative spend through innovation and in the end increase the rate and scale of deployment. While review of historical progress in now large scale technologies is interesting, coming up with a more compelling case for investment for wave energy is existential in nature. Quoceant believe that further work in this important area, with a range of practitioners and experts feeding in relevant experience and input, could be transformational for the sector and reigniting broader investor appetite. Quoceant would be delighted to discuss, frame and contribute such a piece of work if there is appetite for it.