AQUAGEN Report Summary

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Final Report Summary - AQUAGEN (Development of cost-effective, water based power take-off system for marine energy applications)

Executive Summary:

The AquaGen project has developed a prototype water-hydraulic power take-off (PTO) as an alternative to an oil-hydraulic systems. The project has also developed a toolbox of engineering designs, models and manufacturing methods needed to deliver a commercial scale PTO. This has been achieved with funding from the FP7 Support for the Benefit of SMEs programme with the more specific objective of supporting innovative, value-generating start-ups.

The engineering development has been completed with the main purpose of providing a direct comparison of the cost benefits of a water-hydraulic PTO against oil hydraulic PTO for the first commercial scale of the FPP Poseidon P80 (a 1.6MW WEC device). A marketing and exploitation plan has been developed primarily focusing on the wave energy conversion application. The drivers for exploitation for wave energy potentially are:

- Direct capital cost
- Cost and other impact on supporting platform and construction elements
- Operation and maintenance cost
- Efficiency (from wave to wire)
- Power quality
- Simplicity and robustness
- Environmental impact/risks

This engineering development has involved the design, development, testing (lab and offshore) and modelling, and subsequent integration, of key modules, often employing novel technology solutions, in particular:

- A patented wave energy absorber - scale up absorber from P37 to P80, 5kW to 400kW pr. PTO unit
- A novel elastomeric Power Take-Off - scale up 300mm diameter air bags and rolling seal rig to 2m dia
- A water-hydraulic system – scale up 5 kW prototype PTO to 400kW or 1600kW commercial system
- Evaluate an adaptive blade turbine - scale up 50kW laboratory tests to 400kW or 1600kW commercial system
- Investigate a variable speed generator - scale up 50kW laboratory tests to 400kW or 1600kW

The project brought together a consortium of European SMEs, engineering consultants and researchers with the range of engineering disciplines and business foresight necessary to deliver such a complicated and integrated requirement. Floating Power Plant (Denmark) is the technology end-user who potentially will commercially develop AquaGen for the Poseidon WEC, while another SME, Norsistemas (Portugal) will provide electronic components and analysis for remote condition monitoring of the PTO on the platform.

Gilbert, Gilkes & Gordon (UK) are global hydroelectric turbine specialists who are working with the National Technical

University of Greece to design and test a novel variable pitch turbine employing advanced predictive modeling validated on their turbine test facilities. The University of Minho (Portugal) provides expertise in electronics and remote condition monitoring, while Checkmate Flexible Engineering (UK) provides specialist elastomeric fabrication knowledge.

Project Context and Objectives:
The group of SME participants supported by specialist RTD performers comprise the AquaGen consortium aimed to address a major market opportunity by developing a power take-off (PTO) system for wave energy conversion (WEC), with the potential to significantly improved reliability and efficiency of conversion of usable energy while reducing operation and maintenance (O&M) costs, when compared with currently available solutions.

The AquaGen system has at its heart a water-based PTO system ensuring that oil (used in current hydraulic systems) in the ocean will also be fully eliminated, an important ecological requirement for eco-friendly renewable energy sources. There were numerous engineering challenges that the consortium needed to address in both using water-hydraulics and in stretching the efficiency and operational performance gains of the PTO involving a re-design of much of the key mechanical modules, assessment of alternative materials for the overall hydraulic system and evaluation of an adaptive blade turbine design.

The novel components of AquaGen were also modelled and tested and evaluated against operational data and experience gathered over many years on a SMEs partners prototype WEC (the Poseidon P37 platform generating 50kW of wave energy) so that the engineering performance has been both evaluated against rigorous field data and environments and business cost models such that the scale-up of AquaGen can be properly benchmarked against the current oil-hydraulic system. The system and components developed in AquaGen have a broad range of applications, from wave energy, as the main application area, to water desalination and small hydro power generation, and will therefore have the potential to benefit a the SMEs outside of the wave energy market.

The business objectives of AquaGen is to get a direct comparison of the water and oil hydraulic PTO’s for the first commercial scale WEC (the Poseidon P80 platform generating 1.6MW of wave energy) against these metrics:

• Direct capital cost
• Cost and other impact on supporting platform and construction elements
• O&M
• Efficiency (from wave to wire)
• Power quality
• Environmental impact/risks

The engineering objectives and tasks which have been performed and used to develop the scaling rules for each of the major AquaGen modules can be summarised as:

1. Improve wave energy absorber design to maximise energy extraction from range of wave conditions, involving:

- Design and manufacture of novel 5kW water-hydraulic PTO build to operate on an existing WEC (Poseidon P37)
- Extensive laboratory trials on 5kW water-hydraulic PTO to establish dimensionless efficiency characteristics
- Comparison of AquaGen laboratory results with previously collected oil-hydraulic data
- Offshore trials on P37 platform during 2013 to collect actual wave motions and energy (wave force and displacement)
- Development of dimensionless efficiency map to give size of absorber for commercial P80 wave conditions
- Scale up linear to wave front and significant wave heights
- Scale up individual wave absorbers from 5kW (P37) to 400kW (P80)

2. Design of elastomeric Power Take-Off system for water-hydraulics, involving:

- Design and selection of elastomeric PTO for each of the 5kW and 400kW applications
- Scale up 300mm diameter air bags and rolling seal rig to 2m dia
- Development of hydraulic transient analysis network for the optimum design and efficient operation of the PTO over chosen wave conditions
- Establish hydraulic system pressure limit, and so scale up linear with flow, which is (diameter)2, and linear with stroke
- Determine durability of elastomeric components as efficiency is effected by friction and compliance of rubber parts – some aspects linear and some non-linear
- Measured flow versus displacement from 5kW pilot and rolling element rig to indicate compliance
- Compliance scale up based upon elastomer area

3. Hydraulic system scale up from 5kW prototype to 400kW PTO, involving:

- Develop rules for force - displacement relationship (linear)
- Calculate pipework sizing based upon flow velocity (pressure drop)
- Calculate accumulator sizing which is linear with stored volume as pressure is fixed
- Conduct P37 trials (see 1) to give efficiency data for oil hydraulic system
- Conduct 5 kW pilot (see 1) to give efficiency data for water hydraulics
- Evaluate the possibility of variable mechanism or EPTO array to adjust to sea states, ie to expand the effective operating region of the WEC

4. Water turbine design to expand effective operating region, involving:

- Turbine type selection based upon head, flow and efficiency or specific speed
- Manufacture of fully flooded reaction turbine for testing in 50kW flow loop
- Design and material selection of an adaptive blade for novel turbine
- Scale up flow @ pressure using head/flow characteristics from the newly designed turbine
- Develop numerical model of adaptive blade/runner to give high efficiency variable speed
- Scale up 50kW laboratory tested turbine to 400kW or 1600kW PTO

5. Evaluate benefits of variable speed generator: involving
- Originally fixed speed (fixed to grid frequency) – caused issues with hydraulic accumulation/flow control
- Variable speed generator - more expensive but saves cost of hydraulic system, gearbox, inverter
- Evaluate scaling fixed speed – power density, speed, etc

This engineering activity has resulted in:

- Deliverable technical and commercial reports or manuals (typically as Word or PDF docs)
- Design drawing and calculation methods (typically as CAD or Excel spreadsheets)
- Test data (various formats but usually converted for use in Excel)
- Numerical models and associated predictions (various formats).

In addition a useful Excel based ‘Toolbox for the Design of an AquaGen PTO on a WEC’ has been developed for use in the engineering scale-up. This toolbox is complemented by a number of other engineering design and manufacture tools that function on other stand-alone or proprietary operating systems, and a databank of validation cases and scalable test data.

Finally the key cost data (CAPEX, OPEX, maintenance philosophy, etc) have been used in a cost model to judge the through-

life potential economic benefit of the AquaGen system.

Project Results:
The AquaGen project has developed a prototype eco-friendly, durable and efficient water-hydraulic power take-off (PTO) as an alternative to an oil-hydraulic systems together with a toolbox of engineering designs, models and manufacturing methods needed for the SME beneficiaries to measure the AquaGen system against specific cost drivers and so be able to determine its benefits as a commercial scale PTO.

So the S&T development has been performed with the main purpose of providing a direct comparison of the cost benefits of a water against oil hydraulic PTO for the first commercial scale system (the FPP Poseidon P80 a 1.6MW WEC device). This has involved the design development testing (lab and offshore) and modelling and subsequent integration of key modules often employing novel technology solutions in particular:

- A novel elastomeric Power Take-Off - scale up 300mm diameter air bags and rolling seal rig to 2m dia
- Economics for a patented wave energy absorber and cost analysis of AquaGen PTO - scale up absorber from P37 to P80, 5kW to 400kW
- A water-hydraulic system – scale up 5 kW prototype PTO to 400kW or 1600kW commercial system
- An evaluation of an adaptive blade turbine - scale up 50kW laboratory tests to 400kW or 1600kW commercial system
- Other aspects including the development of improved mechanical and chemical properties of elastomers, an assessment of a variable speed generator and a remote communications ands condition monitoring system.

The major S&T objectives of AquaGen have been achieved and are discussed below.

Elastomeric PTO system
The major focus of AquaGen has been the development of an Elastomeric PTO (EPTO) system, and for which a prototype system has been conceptualised, designed, built and tested. Several concepts were evaluated at the start of the project and judged against a number of criteria such as their performance benefits, cost of manufacture and Operating and Maintenance requirements.

The work has resulted in both a design of a sealing seal (Fig 1) that could be used for the commercial scale PTO (that is still being tested) and a prototype that has been integrated into and proven to work at small (lab) scale. For the lab scale work detailed investigation shows that Firestone Airsprings have been used as elastomeric pumps in wind powered water pumping equipment for many years. This meets the primarily requirements for an elastomeric pump unit, in that it exhibits lower maintenance requirements than conventional oil hydraulic cylinders. This is principally due to the fact that the design (a rolling seal) exhibits reduced stress and wear on sealing components compared to conventional piston type seals. Additionally, the working fluid (water) is incompressible and considerably cheaper than hydraulic oil. The combination of the rolling seal element and water as the working fluid have far greater tolerance to contamination and therefore require less filtration and specialized handling.

The water hydraulic solution should exhibit enhanced efficiency due to lower pressure operation, reduced problems through cavitation and the incompressible nature of the working fluid. Water does not suffer from issues of foaming or deterioration in the same way as hydraulic oil, and so the life of the working fluid should be enhanced by the adoption of a water hydraulic Elastomeric PTO.

Finally the Elastomeric PTO using water as a working fluid is more environmentally acceptable than conventional oil. This is because a potential failure in the PTO structure or any part of the hydraulic network would result in the escape of the working fluid, which for AquaGen is water.

Integrated Economic Model

A sophisticated ‘unitised’ cost model has been developed by FPP and used to compare the through-life costs of the water and oil hydraulic PTO systems within an overall cost model of the complete Wave Energy Converter (WEC)

The analysis (and comparison between the water and oil hydraulic solutions) uses a combination of laboratory and offshore test data and the engineering scale-up rules. To perform an objective comparison of the developed EPTO system to the existing oil hydraulic system on a commercial scale (P80) at an engineering design level the following comparison parameters were selected. These parameters were used to compare the two PTO’s, ie not the complete WEC.

Direct capital cost - The direct costs of materials and labour to build the EPTO system and install it in the device
Cost and other impact on supporting platform and construction elements - Estimated cost of necessary changes to the existing platform design. Not engineering costs only changes in the construction cost
O&M (Cost (direct and indirect), Safety, Life expectancy, Up time) - Assessment of impacts on O&M relative to the existing oil hydraulic system.
Efficiency (from wave to wire)
Power quality (power gradients) - Power buffer capacity to satisfy grid demands
Simplicity and robustness – Standard or non-standard components, parts, methods, etc

As an example, in terms of hydraulic pipeline, two options were investigated: GRP pipe and PVC pipe
As most of the components used in the P80 AquaGen system are not available off-the-shelf, a scale up extrapolation has been used to estimate the price of the systems. The table In Table 1 summarises the difference between the two potential systems, in terms of base cost and maintenance cost (planned and unplanned).

In terms of maintenance, the accumulator must be pressure checked every three months for operational safety, a significant check of the hydraulic circuit should be carried out at the same time in order to unplanned maintenance cost. If any major concerns are observed, the EPTO housing should be replaced. As the EPTO housing is a separate structure attached to the P80 platform, the opportunity of changing it quickly and easily exists; all offshore planned or unplanned maintenance should not affect the production of each platform.

Moreover as the rolling seal element lifetime target is only 3.5 years replacing the rolling seals at the end of their useful life has an estimated cost of 650 000 €. Some potential methods as mentioned in AquaGen deliverable D6.5 may be able to improve the lifetime of the seal and these methods should be fully investigated before full scale production commences.

The electrical control systems will be similar for oil hydraulic and AquaGen EPTO applications, therefore the power quality should not be affected by either solution.
In terms of efficiency, as mentioned before, a higher peak can be targeted (70% compare to 64%) and so the peak production should be higher.
AquaGen Water Hydraulic EPTO’s have a higher capital purchase value than oil hydraulic systems. The major benefits of the system will be in reduced maintenance and higher production efficiency. Greater confidence in the pricing structure is required to prove the capital costs since there are very few “off the shelf” components in the AquaGen system, estimated costs have been used which may prove to be too high when a full production model is completely investigated. The commercial sensitivity of the designs has prevented the full scoping and cost assessment.

In order to make a fair comparison of the cost of the two different PTO systems a common cost model spread sheet was set up. This cost model takes into account all the sub components that might differ between the two systems. Apart from the direct capital cost (construction price) the expected maintenance intervals and associated costs are also registered in this model. This is described further under O&M

In Tables 2 and 3 the direct costs for the two systems is shown.

It can be seen that the cost for the EPTO system is significantly higher at almost double the price. The most significantly difference is due to the hydraulic system. The higher cost can be attributed mainly to two factors.

First the EPTO technology is a novel solution and so the design is sub-optimal and currently uses many non-standard components. In contrast the oil hydraulic PTO consist almost entirely of widely available industry components. The other reason is due to the significantly lower hydraulic pressure in the EPTO system. This requires very large components to handle the larger flow in the EPTO System.

This does however mean that there are still significant cost reductions for the EPTO system, when production is scaled up from the first plant to series production.
The work also considered cost and other impact on supporting platform and construction elements. No differences in impact of the platform structure have been identified. The central turbine/generator unit setup proposed for the EPTO including the necessary accumulator capacity is not expected to increase the construction price of the platform significantly.

The operation and maintenance costs have been estimated using the unitised cost model. In the O&M section standard rates for different categories of service personnel and service vessels have been used for both systems. Originally it was the plan to estimate both planned and unplanned O&M. However it was assessed that a sufficiently good basis for estimating the unplanned O&M didn’t exist for either of the systems, so this will be considered outside the current project.
The O&M costs are given for the different sub systems as direct cost covering the cost of necessary personnel, vessels, exchange parts and materials, and indirect costs covering production loss due to maintenance. According to FPPs strategy each PTO module/ absorber assembly are to be serviced in harbour with 3.5 year intervals and the whole platform with 7 year intervals. Maintenance activities are primarily planned to follow these intervals to reduce the production loss and avoid the high cost of doing service offshore.

The O&M costs for each system are shown in Tables 4 and 5. Again it is seen from these tables that the EPTO system is significantly more expensive to maintain. A big cost driver is the need to replace the rolling seals in the EPTOs every 3.5 years. This alone account for more than 3,000,000 EUR of the total budget.

It has to be stressed that the O&M cost calculation is based on estimates of the life expectancy of the sub components of systems that are not engineered in detail and is operating under conditions not known in detail. The costs are therefore associated a lot of uncertainty. The reliability of the cost of maintaining the oil hydraulic system is likely to be more accurate since more experience exist form the operation of similar hydraulic systems. The price for the EPTO system maintenance may therefore be overestimated.

It was not feasible to model the complete system including the wave absorber and so it was not possible to give an accurate efficiency matrix fort either of the systems. However the efficiency of two systems has been estimated from the small scale systems. The shaft to generator efficiency of both systems has been estimated to 70% with a margin of error of +/-5 percentage points. Hence it does not make any sense to calculate the potential energy production of the two systems. The economical comparison can therefore be limited to the cost alone.

Both systems use similar drive / inverter systems. These inverters are designed to meet the TSO demands for most power quality parameters. The only power quality demand governed by other system components than the inverter is the active power gradient. This is primarily governs by the accumulator capacity. Both systems are estimated to be able to meet the power gradient demand from the Danish TSO Energinet.dk with reasonably sized accumulators. The cost of the accumulators is covered by the respective price estimates.

The EPTO system is expected to have a higher number of mechanical components, sensors and actuators than the Oil hydraulic system. Furthermore many of the components for the EPTO are purpose manufactured an non-standard component types. The oil hydraulic system in comparison consists almost entirely of widely available standard industry components. All together this gives a significantly higher technological risk for the EPTO solution. The mechanical robustness / durability of the two systems is expected to be similar when the systems are maintained properly.

The use of a single turbine/ generator unit in the EPTO increases the risk of production loss in the event of a fault in the turbine/ generator unit or pipeline.
The hydraulic networks of both systems are enclosed in the PTO modules and platform structure. This greatly reduces the risk of spill to the environment in the event of a leak. However the use of water a medium in the EPTO gives a much greener profile and eliminates the negative consequences of a spill.

The cost calculations show a significantly larger price for The EPTO system both in investment and O&M. To put these costs in a broader perspective the numbers was integrated into FPPs project economy model. This model takes all aspects of a project from concession to decommissioning into account. Key numbers for four generations of devices of development are calculated. Assuming that with each generation the devices is deployed one larger and larger arrays a general cost reduction from series production is obtained the following assumptions was made.

It can be seen in Table 6 that greater scale up cost reductions is expected for the EPTO system compared to the Oil hydraulic system, both for investment and O&M. The reason behind this is that series production is expected to reduce the component cost. And that experience from operation of the early EPTO systems will lead to more durable components with reduced maintenance costs. All other assumptions were held identical between the two systems.

Table 7 shows that even though the initial investment for the EPTO system is almost double that of the oil hydraulic system and that the O&M costs are even higher, the unitised cost of the total energy mix from the first generation plant is only 18% higher. The margin between LCOE using the two different technologies shrinks even more in later generations assuming higher cost savings for the EPTO system.

Hydraulic system design

Several power take off methods exist to convert the normally linear motion of a wave energy absorber into electrical energy. The most widely used are hydraulic systems, which involve an intermediary conversion of rotary motion. Alternatively, there are direct drive systems such as linear generators, magneto hydrodynamic generators and contact-less force transmission systems. Hydraulic systems are usually relatively inexpensive and have a wider proven track record, but due to the conversion process being indirect, its efficiency is reduced. Losses occur during pumping and turning the hydraulic motor in addition to the losses present in the generator and inverter. Also, hydraulic systems are usually designed to work at lower speeds than those typically experienced by wave energy converters.

The challenge for AquaGen was to match or better the hydraulic system that has already been developed for the Floating Power Plant P37 prototype system and then demonstrate both the performance (conversion efficiency) and cost benefits (CAPEX, OPEX, O&M, etc). This has been met through an extensive process of systems and engineering analysis. The hydraulic system design has been created by VP using Flowmaster a proprietary transient hydraulic analysis simulation and is composed of an integrated hydraulic design composed of discrete components (pipes, values, losses, etc) that is used to predict the variation in flow and head through the hydraulic system.

The simulation relies on the assumed operating characteristics of these components and on dynamic input data derived from various sea states collected from the P37 prototype WEC and the WEC mechanism designed during the project. The software is capable of highlighting potential hydraulic failure points within a given system and will highlight these and allow design

iterations to be added in order to produce a verified computer model of the system. Parameters including surface roughness, pipe lengths, accumulator volumes and system pressures can be added or altered to enable the user to define a hydraulic network and run a simulation of the system in operation. The hydraulic network developed is shown in Fig 2.

Different regional operating environments have been defined using actual, but limited sea-state data and this data coupled with the predictive tools such as computational fluid dynamics (CFD) and pipe network analysis models, developed for the project, have been used to predict the performance of several PTO designs under a variety of normal and extreme sea-state operating conditions. An example of the design considerations for sizing an accumulator in the PTO system, based on a hydraulic analysis are shown in Figure 3 below. Here it is shown that under these sea conditions there are large fluctuations in the flow to/from the accumulators and so will give an unstable flow to the downstream water turbine resulting in inefficient energy conversion. So the design tool will help to optimise the hydraulic design to maximise conversion efficiency/power quality for the sea state conditions at specific locations that the commercial WEC.

The hydraulic system has been further developed for the AquaGen project to be an adaptive system which addresses the issues of scale up through the design toolbox developed during the project. Flow and pressure required to generate potential supply voltage and current produce results which indicate the size and volume of the hydraulic system required. Initially, for the purposes of the tests and proof of concept, a hydraulic system with 4 EPTO’s was developed (see Fig 4).

The hydraulic system that was tested in the 5kW PTO test device was only controlling 4 EPTO’s with bypass capability for one pair of EPTO’s. Development and scale up for the 400kW full scale production device uses 23 EPTO’s of different sizes manifold together and coupled to generators (see Fig 5). This system has greater control requirements than the hydraulic system constructed for the test device. In this scaled up design, there will be a requirement to bypass several EPTO’s in different wave states.

The simulation tool can also in future be used to predict system performance for new WEC locations and/or refinement of the hydraulic design and components and has been made available to the SME beneficiaries to verify changes in flow and pressure. The software is capable of highlighting potential failure points within a given system and will highlight these and allow design iterations to be added in order to produce a verified computer model of the system. Parameters including surface roughness, pipe lengths, accumulator volumes and system pressures can be added or altered to enable the user to define a hydraulic network and run a simulation of the system in operation. Flow and pressure outputs are provided which can then be matched against a turbine selection table (see Fig 6a).

From the hydraulic design data a new, optimally designed, model turbine runner was successfully fabricated and installed in a Francis test rig of NTUA. The equipment calibration and the measurements conducted were conforming to the IEC60193 acceptance standards. The experimental uncertainty of the efficiency data was calculated below 0.8%. The new model turbine was thoroughly tested in a wide operating range, by varying the rotating speed of the feeding pump or the generator, as also the opening angle of the wicket gate vanes. In all these conditions the performance of the runner was smooth, without any instabilities or vibrations, and no cavitation was visually observed at blades outlet section or in the draft tube. The measured maximum overall efficiency of the turbine almost coincide with its design point, thus verifying the effectiveness and reliability of the numerical design procedure (described further on), as well as the correct fabrication and installation of the model.

Finally, the comparison between the measurements and the numerical predictions showed satisfactory agreement, hence verifying the applicability of the numerical tools developed and applied in this project for the optimum turbine runner design to both the model and the full-scale turbine.

Using these selection tools and iterative processes, the optimum power output can be targeted from a known wave state and deflection angle of the floater. This tool will allow the WEC SME to tailor their designs to a proposed geographical location knowing the wave state.

Results from the sea trials have been used to confirm or adapt the design and other aspects of the AquaGen hydraulic system and to verify the scale up criteria for the first commercial WEC (a 400kW PTO). Sea conditions from prospective locations for the first commercial WEC have also been used to scale up from the P37 to the P80.

Adaptive blade turbine design

The optimum design and attainable overall efficiency of the turbine in the AquaGen application is a function of the requirement to operate in a wide range of loading (flow rate) conditions, not only due to the variable wave power input, but also due to possible pulsating flow in the EPTO system. Further improvement of the overall efficiency and maximization of the annual energy production of the turbine needs to be met by ensuring that the rotation speed of the turbine is varied in continuous mode. In this way, the turbine could rotate with the optimum speed at any off-design operating conditions.

The present turbine for the EPTO system is a low specific speed Francis type, with a fixed geometry which is perfectly adequate for certain offshore locations. However, a considerable increase of efficiency could be obtained if there is a capability to adaptively change the outlet angle of the runner blades, so the outlet velocity triangle remains orthogonal and the flow leaves the runner with almost zero circulation. However, this is not feasible for small size turbines and even more when the specific speed is small, like the Francis type hydroturbine examined here. The blade adaptation technology has been demonstrated to be viable a tlaboratory scale and so deigns have been developed in order to be applied to large scale hydroturbines.

The dimensions of the full scale runner and the 400 kW reaction turbine can be produced by geometric similarity from the model turbine which was designed by numerical analysis and optimization methods in a previous task (Deliverable D5.3). The scale-up factor was set to 1.5 namely the dimensions of the 400 kW turbine will be 50% larger than the model turbine as can be seen in Table 1.1. This relatively small difference in size compared to the large difference in power (400 kW versus 67 kW) is due to the double rotation speed of the full-scale turbine (1500 rpm) thanks to which the size of the turbine and the generator is kept small.

Although the design of the runner blades for the full-scale runner could also be obtained by the same geometric scale-up rule from the model runner, an additional numerical optimization cycle was carried out to achieve finer tuning of the exact blades shape, and take into account the effects of scale on the efficiency in a more direct way. Moreover, the weights used in the objective function for the multipoint design optimization of the model runner, were approximated and do not correspond to the real data that was agreed to be used in the last project meeting.

The new weighing factors were extracted from the EPTO data supplied by the VP, that are based on absorber deflection time series data, taken from existing off-shore sites, which are used as input to the modeling tool of the EPTO system, developed by VP.

For the full-scale system the stroke volume is quite large, and hence a pressure vessel capable to stabilize the flow conditions at the turbine inlet should have very large capacity and size. In order to reduce these storage needs of the EPTO system, the following technique is proposed.

The hydroturbine can follow the flow rate variations in the main hydraulic system, imposed by the wave converters, since the loading (and unloading) rate of a 400 kW Francis turbine is quite high: a few seconds from minimum to maximum load. This can be achieved by continuous variation of the wicket gate vanes angle, using an automated control system and sensors of pistons motion. The response time of the turbine to start regulating its guide vanes is small: usually it is taken up to 0.5 sec, and it could become even smaller, with modern electronic control.

Hence the flow volume to be stored in the pressure tank can be quite smaller than the stroke volume of the pistons as shown

in Fig. 7 (only the shaded area). In addition the use of expert algorithms to simulate and predict the wave power and piston motion (e.g. neural network software) could further reduce the gap between these two curves and hence the storage capacity of the pressure vessels.

The annual flow duration curve in the system and through the turbine can then be produced by post processing of the data, whereas a constant pressure can be approximately assumed. The same method could be applied also to avoid the development of higher pressures at the turbine inlet.

The annual flow duration curve in the system and through the turbine can then be produced by post processing of the data of first and second Table 9 and 10, whereas a constant pressure can be approximately assumed. The zero pressure values in this Table indicate flow rate conditions well below the technical limit of the turbine, where it can be by-passed and does not produce energy. The same method could be applied also to avoid the development of higher pressures at the turbine inlet.

In order to simulate the turbine operation for a number of different operating points and then apply a multipoint design optimization procedure, six successive regions were defined and used to represent approximately the computed flow duration curve:
a) <15%, of the nominal flow rate (550 lt/s)
b) 15 to 45% of Qn
c) 45% to 75% of Qn
d) 105% to 135% of Qn, and
e) > 135% of Qn

The cumulative fluid energy available to the turbine within each of the above regions is then computed and the obtained results are plotted.

After the adjoint-based optimization algorithm, the performance of the optimized turbine geometry is presented in the following table. It is seen in Table 10 that the efficiency has decreased for the first two operating points and increased for the last.

For a better understanding, four single point optimization runs were performed, aiming at efficiency maximization of each corresponding point. The turbine performance of the four optimized geometries obtained is presented in the following Tables 11.

The efficiency of each operating point examined is maximized, as expected. The performance at the point corresponding to the 90% of the nominal flow rate does not vary substantially in the four optimizations performed. Taking into consideration that this point is near the nominal operating conditions, it is concluded that the starting runner geometry was well designed for the nominal point and, thus, it takes not too much of improvement.

The fourth operating point (120% Qnom) seems to be dominant between the other four, as it is the one improved most. However, by optimizing separately the efficiency of this operating point, the efficiency of the first two (which correspond to the 30% and 60% of the nominal flow rate) decreases. This is explained in Fig. 8, where the four optimized runners obtained are compared with the starting geometry. It is clear that to improve the runner operating at 30% and 60% of the nominal flow rate, the trailing edge needs to move downwards, while for increasing the efficiency at 90% and 120% upwards, namely to the opposite direction. This conflict between the operating points' efficiency misleads the multipoint optimization. The greatest weight is on the operating point which corresponds to the 90% of the nominal flow rate and at the weighted sum of the objective functions gradient, the final displacement of the blade favors the last two and leads to the decrease of the efficiency of the operating points at 30% and 60%.

For the sake of completeness, another multipoint optimization was performed, examining the two operating points corresponding at the 30% and 90% of the nominal flow rate. The weights used here were 0.7 and 0.3 respectively, and the performance of the optimized blade for all the operating conditions are presented in the following table. Having given greater weight to the operating point at 30%, the blade's displacement was in the opposite direction, which led to the improvement of the first two operating points.

In Fig. 9 the pressure distribution in the runner is shown for the starting and the optimized cases. From these figures we can see that the pressure distribution is not significantly affected by the changes in shape. This is expected as the efficiency differences which were achieved are small. However, a small difference for the cases of 90% and 120% flow optimizations is observed. the cumulative displacement of the pressure and suction sides are shown for two different optimization cases. From these figures we can see that the majority of shape change takes place in the area near the shroud of the turbine, and it is more pronounced for the case of 90% flow optimization. This shows that the efficiency is more sensitive at low flow rates, as smaller shape adaptations have larger effect on the efficiency. This behavior was expected, since the efficiency curve of the turbine is steeper for lower flow rates. Furthermore, the turbine is designed for the nominal operating point and thus to achieve noticeable improvements in efficiency, relatively higher changes are necessary.

Finally, an alternative way to improve the productivity of the PTO system is the installation of multiple turbines instead of a single machine. For example, a larger PTO system of 1.6 MW will contain four 400 kW hydroturbines, thus providing significant production flexibility. In that case, every turbine will not have to operate below 75% of its nominal load, and hence its efficiency will be kept quite high. Moreover, this practice can extend further the operating range of the system, at even smaller or higher percentage loadings.

AquaGen Design Toolbox

Following recommendation from the independent reviewer the AquaGen consortium integrated many of the design tools developed into a toolbox (Fig 10) that can be used by the SMEs to support their design evaluation and detailed engineering operations.

The work packages of the AquaGen project have created a large amount of data which is relevant to each segment of the iterative design process. These data have been collected into an Excel based format which allows selection of criteria based on input data from the user. The toolbox comprises:

- AquaGen hydraulic system
- Power generation and calculation of system efficiency
- Available wave power
- Floater efficiency and angular deflection
- Elastomeric power take off
- Design and sizing
- FEA Simulation
- Hydraulic circuit sizing
- Pipe sizing
- Non return valves
- Accumulator sizing
- Hydraulic circuit simulation
- Software used
- EPTO simulated as an Input flow rate
- Turbine simulation

The toolbox can be used in order to scale an AquaGen system for a WEC and in order to match a certain generated power. Users may add parameters and/or alter parameters in order to achieve a design specification for a given location. This will provide an initial sizing and power production which may then be used as a design start point, or alternatively as an economic

validation of a given wave location. This tool box is not proposed as a final design iteration tool, but as a step in the design process to validate the suitability from a power production and economic scoping perspective.

Protective barrier coatings and fillers for marine resistance of elastomeric structures

One of the novel aspects of the AquaGen project was the development of light weight and replaceable elastomeric components capable of operating in exposed positions which at sea means being exposed to salt spray, potential bio fouling and UV and IR attack. This specific requirement has been avoided by moving these components into an enclosed location and so the requirement as replaced by developing filler materials with the potential for greater wear resistance. Specifically, the motion of the rolling seal element proposed in the AquaGen project involved contact between the seal and 2 other components, the piston and the cylinder. An important part of the work was to select the best sliding/rolling material combination to reduce friction coefficient and to increase wear resistance.

Based on the potential improvements that may be gained through the inclusion of nanoparticles, it has been chosen to focus on adding nanoparticles of graphene to the selected rubber for the manufacture of these components. Different methods of incorporation of nanoparticles into the elastomeric structure have been investigated. Graphene demonstrates high elasticity and can potentially be elongated up to 20% of its initial length before the bonds fail and the material breaks. Therefore grapheme was considered a suitable as a candidate in making a new generation of super strong composite materials with enhanced flexibility. It has been demonstrated that graphene acts as reinforcement in epoxy based composite. It has also been demonstrated that the reinforcing efficiency of graphene in the composite depends on the thickness of graphene.

In a rolling seal application, the mechanical properties are provided by the reinforcing nylon textile, therefore its stiffness and strength determines that of the seal. The rubber coating serves to provide a matrix to hold the structure together and provide air holding, and protect the nylon from wear. Due to the cyclic motion of the seal, the fatigue resistance of both elements are important. Several methods of incorporating the nanoparticles into the process oil were investigated. These ranged from use of a WAB stirred bead mill to ultrasonification mixing techniques. However it was finally realised that for commercial scale mixing, it would be equally as effective to add the nanoparticles as dry powder into the mastication process, since rubber manufacture is a high shear process.

A new filler and cost effective method of its incorporation into rubber like materials have been developed. The recommended mixing method would be to treat the graphene powder in the same way as the carbon black used in conventional rubber compounds and add it in the internal mixer along with carbon black and process oil as soon as the polymer has been broken down and is in a softened and warmed up masticated state.

Customized monitoring system

The main goal of the signal analysis software is to develop a system that allows wave energy platform operator to monitor what’s happening on individual WECs no matter where they are located around the world. Using a web browser it should be possible to monitor the state of each platform (WEC). It is anticipated that the connection to all platforms should be done by 3G network allowing remote connection without the need of implementing wired infrastructures.

Data generated from each platform should then be processed by a server that saves it in a database. Then the operator can use a web application to display the information. An architecture that can do this job and at same time adds some new features has been implemented. In Fig 12 an overview of the system is presented.

Basically, each WEC platform will have a “Platform System”, represented on the left side of Figure 12 that will communicate with a central PC server. This central PC server will have 4 main goals which are: host the website, host database, host a web-service, run an application that will deal with all platform connections, deal with database and also with some web service methods.

The Platform System runs on an industrial PC, which gives us all support to control the platform and also to monitor its performance. A windows service application, which runs without user input, is responsible to sample all the used sensors, save values locally, send it to the server computer and then implement in the platform. This is the heart of each platform and as it does not need direct user inputs to work it was implemented as a service.

Its main function is to sample each sensor, save locally the information and in a defined period send it to the central server. To do this and at the same time be ready to accept with minimal changes platform control, real sensors and at the same time be configured by the website or other application, we created inside the service a structure of interlinked classes.

The parent class is the Platform's class (Fig 13). In this class, all platform relevant details are stored, such as the platform ID's, Server IP's, sensors list, etc. This sensor list, is a list of objects from Sensors class. Sensor class represents an individual sensor, and due to this, it contains exclusive sensor information like type, state, ID, limit values, and sampling times. Each sensor has its own sample list that it's based in other object from a class registers.
As a windows service application is a program that runs in background, without any user graphic interface, there is a need of having one GUI to give the change to configure and inspect the platform to someone that is inside platform, to fix or configure locally the platform. It's also useful for debug. This application has a main window with some tab controls that represent some of the different functionally.

This configuration was not progressed beyond the 'bread board' phase because the offshore sea trails were cancelled and so the remote condition monitoring was not implemented in the project.

Variable speed generator design

It was initially envisaged that the AquaGen project would lead to the development of hybrid variable speed generators. This was particularly pertinent for the original wave energy converter (WEC) design and ethos; however there was a change in WEC provider mid-way through the project. Additionally there was a change in the SME responsible for the hydro generators at an earlier stage in the project (IT Power). This lead to a gap in the consortium capabilities; IT Power were replaced in the consortium as an SME by Gilbert Gilkes and Gordon who manufacture hydro turbines. They do not however have expertise in generator design and construction. As a result of this withdrawal, the work on variable speed generators was effectively halted. There are commercially available variable speed generators on the market and also other control mechanisms are feasible to control the generator speed. During the course of the work a PTO test bed was constructed which included control mechanisms familiar to the new WEC manufacturer. These control mechanisms are commercially available systems, in this case from Siemens, which control the generator speed and output relative to the incident torque on the generator drive shaft.

The use of variable speed generator, along with the electronic control equipment for optimal speed adjustment, can increase significantly the cost of the generator (of the order of 100% or more). Hence, the potential improvement in the overall efficiency must be investigated and quantified.

Potential Impact:
Commercial Impact: EU Directive for National Renewable Energy Action Plans (NREAP) projections (Ref 1) required member states to submit their plans in accordance with the template published by the European Commission (EC), and provide detailed roadmaps of how each Member State expects to reach its legally binding 2020 target for the share of renewable energy in their final energy consumption.

In comparison to the NREAP projections for wind energy of 213GW installed capacity in 2020 supplying 14% of Europe's total

electricity demand the EU Member States NREAP projections on aggregate indicate that the installed capacity of marine energy in 2020 will be 2.5GW supplying approximately 0.15% of the total EU electricity consumption. This was evidence that at the commencement of the AquaGen project marine energy technologies were still very much emerging with high associated costs and uncertainties.

Potential priorities to deliver the greatest benefit to Europe requires innovation support across various stages of technology development and is needed to play a role in reducing cost of energy and risk, with the later stages having the highest innovation costs. Completion of the AquaGen project and associated reduction in the technological uncertainties together with the continued commercialisation of the existing wave energy converter (WEC) platform that AquaGen has been designed to integrate into means that the SME partners, and the Poseidon platform in particular can have an enormous benefit for Europe both in terms of market penetration, meeting member states CO2 reduction targets and off course helping with EU energy security.

Considering only the market for marine renewable energy. One of the major differentiators of the commercial WEC system (Poseidon P80 owned by SME partner Floating Power Plant (FPP)) is that it is designed to operate in significantly deeper waters than many of the competitive systems. The mooring system allows the P80 to operate in water depths greater than 40m making this a system that can be moored out of sight (ie over the horizon from the shoreline) and in deep water regions with higher wave energies.

An analysis of offshore developments in the European North Sea shows many locations for offshore wind and from which P80 will position its unique hybrid wind and wave system to respond to these emerging needs. There are around 150 new wind parks currently planned / consented and these show a scarcity of available of wind sites near shore. As a result our market assessment indicated that marine energy parks (including wave) commissioned for 2017 or later are being pushed to water depths greater than 45m.

The use of a tethered (anchored) system to position the Poseidon P80 platform negates the limitations confronting foundation based energy conversion systems and places it in a strong position to exploit many of the European licenses that will be open to tender in the next few years. Discussions are currently underway with several European national agencies where the P80 system will pre-qualify for selection ahead of competitive bidding for offshore leases.

Looking globally our market assessment has identified several locations where Poseidon has clear advantages over the competition and the second wave of exploitation will explore these. To this end FPP has set up a joint venture with an Oregon company to exploit the wave energy technology off the West Coast of the US.

Aside from, or as a by-product of wave energy conversion there are several other markets/products that the IP developed for the AquaGen partners may be exploited in. At present there are several options for the commercialisation, eg product offering, route-to-market, value proposition, etc of the AquaGen IP and so a few of the key opportunities summarised here are:

- Desalination - based on the direct pressurisation of sea water (avoiding the generation of electricity) that is then fed into a reverse osmosis (RO) desalination plant to produce fresh water. There are many water stressed regions of the world on the coast for which near-shore RO using wave energy conversion has immense potential. SME partner FPP and RTD performer VP from the AquaGen are currently engaged in an engineering feasibility study as part of the EU funded H2Ocean project to commercialise integrate the Poseidon platform into an offshore fresh water factory.

- Hydrogen Production – also within H2Ocean using conversion of energy into hydrogen that can be stored and shipped to shore as green energy carrier

- Micro-hydro - Although an established technology, the drivers of research activities for small hydropower aim at developing

technology innovations that will lead to cost reductions, especially in low-head schemes; local environmental impact minimization; and increasing efficiency and reliability , all of which are key issues addressed in AquaGen. More than 30 companies compete in the European small hydro market, where the opportunities for SME partner GGG will arise from the refurbishment and replacement of existing plants, with clients aiming to achieve the best possible efficiencies and capacities.

Political impact: Conversion of energy from wave to electricity around the coasts of member states supports the renewable energy policy in European member states that has emerged primarily from Directive 2009/28/EC. AquaGen give member states with suitable coastal waters a new option in meeting their obligations while maintaining energy security needed for growth and quality of life.

Energy security impact: In comparison to the National Renewable Energy Action Plans (NREAPs) projections for wind energy of 213GW installed capacity in 2020 supplying 14% of Europe's total electricity demand the EU Member States NREAP projections on aggregate indicate that the installed capacity of marine energy in 2020 will be 2.5GW supplying approximately 0.15% of the total EU electricity consumption. This was evidence that at the commencement of the AquaGen project marine energy technologies were still very much emerging with high associated costs and uncertainties. The pathway to marine energy is ambitious but conceivable and only possible with significant innovation and so long as there is continued national and European wide support in prioritised innovation areas. The support through the Framework Programme and other national programme has ensured that the Poseidon system and AquaGen had gotten closer to market and hence will make an impact on delivering economically competitive reliable and secure source of energy.

Job creation and the growth of SMEs: The SME consortium aims to exploit the European market themselves during the first 5 years post-project, engaging with other European SMEs when necessary to guarantee the production and distribution of both the PTO system and its components, for the different end-user segments. It is still currently uncertain what the direct jobs growth will be as the core business model (of FPP in particular) is based on much of the production/servicing being sub-contracted or even the technology being licenced to third parties. From year 1-2 post-project, the SMEs will consider wider exploitation possibilities (see Commercial Impact). Primary issues to be considered here include the licensing of component production to European SMEs with a view to addressing markets outside Europe. This possibility will be pursued as soon as possible after market breakthrough and the identification of another suitable value chain.

Water stress impact: Producing drinking water from seawater is a good method to alleviate water stress in arid regions located near the sea. The AquaGen PTO as part of the Poseidon energy converter may be a cost effective energy source and which is now being explored by AquaGen partners in several other projects including H2Ocean (GA No 288145) – which is developing a concept for an open-sea platform for energy conversion and NAWADES (GA No 308439)– which is focussed on membrane filtration technologies. The current wave-powered desalination technologies are based on modifications of wave energy technologies designed for electricity production. Therefore, they are typically relatively large with unit capacities in the range of 500– 5,000 m^3/day. Thus, the primary target of wave-powered desalination plants is municipal-scale water production. Year 1-2 post-project the outputs from H2Ocean will help guide FPP on the technical feasibility and economic viability of the Poseidon WEC for this purpose.

Energy stress impact: Distributed micro-hydropower generation is a possible use of the higher efficiency. Lower cost material developments made possible through AquaGen. For micro-hydropower generation to be exploited by the SME partner GGG the new turbine concept developed in AquaGen needs to achieve a significant market penetration. One of the major barriers for any business is that the target market for many of these micro-hydro devices is poor communities in rural areas (ie without infrastructure). An important success factor for the high penetration rate of micro-hydro in these regions will be very low up-front cost of the Chinese imported equipment which cost only 10% of a similar sized ‘western manufactured’ unit, thus making it affordable for rural families. These price differences make it difficult for manufacturers of higher quality products to compete making the benefits of the water-turbine technologies developed through AquaGen at this point uncertain in all but developed regions of the world. The global reach and locate distribution by Gilkes makes it possible that Gilkes could manufacture a

‘simpler’ turbine locally, but this is still something Gilkes will need to consider carefully as their brand is built on a 150 years reputation of high quality manufacture and equipment/system reliability.

Main dissemination activities

Exhibitions including Scottish Renewables, Edinburgh, 2013, HydroVision International, Colorado, 2013

Presentations to technical and business communities including national government and EU ministers, business leaders and potential supply chain partners

Website: https://sites.google.com/site/aquageneu/ with links to all project partners websites

Leaflets and presentations including annual newsletters, press releases, presentations on technical developments and progress

Videos of prototype platform during sea trails and the P80 concept (on FPP website) and of PTO during testing (on AquaGen website).

Main exploitation of foreground will be through the use of the design drawing and calculation methods (typically as CAD or Excel spreadsheets), test data (various formats but usually converted for use in Excel) and Numerical models and associated predictions (various formats) to support the design of the complete PTO system for scale-up to a commercial Poseidon system. A ‘Toolbox for the Design of an AquaGen PTO on a WEC’ has therefore been produced containing the engineering methods employed in the design of both the 5kW prototype PTO/floater and the full scale 400kW PTO/floater. FPP will use this design tool to establish if AquaGen technology is:

- More efficient
- More robust
- More cost effective
- And can meet platform and grid demands

Compared with the current oil-hydraulic solution. A secondary goal is that if this technology proves better, to potentially sell or licensee the system to other wave technology developers.

There are other design, selection and manufacturing tools available for the SMEs to exploit the design knowledge developed on specific PTO components namely:

- Hydraulic system design
- Elastomeric PTO system manufacturing methodology
- Variable speed turbine design
- Adaptive blade turbine design
- Protective coatings or formulations in elastomers
- Customised wireless monitoring system

For SME partner Gilkes the AquaGen project has helped to develop the hydraulic and materials engineering requirements for water turbines. The use of new materials may also lower production costs compared to today’s technology, and require less time to form into the desired shape compared to steel (polymer or composite materials are more easily moulded into a final shape). These benefits both for the WEC application and existing customers and new markets/applications will be explored.

For SME partner Norsistemas the application of their existing Radio Frequency Based Technology (RFBT) capability for ‘over the web’ real-time condition monitoring of equipment or processes presents a new business opportunity. NS will use the results from the AquaGen project to confirm the technical viability of their systems (hardware and software) and consider its use for condition monitoring in other industrial applications.

The SME partners will be free to decide what design and manufacturing products/processes from the toolbox they need to integrate into their in-house engineering capabilities and which of these they intent to continue to source through external expertise.

List of Websites:
https://sites.google.com/site/aquageneu/

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Related information

Result In Brief	Green alternative for hydraulic system

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