This title may appear rather presumptuous in the light of the progress made by the leading wave energy devices. However, there may still be some useful lessons to be learnt from current ‘offshore’ practice, and there are certainly some awful warnings from the past. Wave energy devices and the marine structures used in oil and gas exploration as well as production share a common environment and both are subject to wave, wind and current loads, which may be evaluated with well-validated, albeit imperfect, tools. Both types of structure can be designed, analysed and fabricated using similar tools and technologies. They fulfil very different missions and are subject to different economic and performance requirements; hence ‘offshore’ design tools must be used appropriately in wave energy project and system design, and ‘offshore’ cost data should be adapted for ‘wave’ applications. This article reviews the similarities and differences between the fields and highlights the differing economic environments; offshore structures are typically a small to moderate component of field development cost, while wave power devices will dominate overall system cost. The typical ‘offshore’ design process is summarized and issues such as reliability-based design and design of not normally manned structures are addressed. Lessons learned from poor design in the past are discussed to highlight areas where care is needed, and wave energy-specific design areas are reviewed. Opportunities for innovation and optimization in wave energy project and device design are discussed; wave energy projects must ultimately compete on a level playing field with other routes to low CO\textsubscript{2} energy and/or energy efficiency. This article is a personal viewpoint and not an expression of a ConocoPhillips position.

Keywords: wave energy; offshore; structures; design

1. Mission

Offshore structures are designed to provide working area and carry weight; this is mostly above water level and hence they must pass through the sea surface. To reduce wave loading, they are designed to interact with waves to the minimum extent. Subsea oil and gas technology eliminates surface structures, reducing...
capital cost, while generally making intervention more expensive, and is routinely used for step out wells. Some subsea tools and technologies may be used in wave energy, particularly power transmission and subsea intervention techniques.

For high efficiency, wave power devices must interact to the maximum extent with small to moderate waves and be good wave makers; large device displacements are generally required to radiate cancelling waves up- and downstream and these large motions in moderate waves violate linearity assumptions, making analysis more difficult. Devices should not interact strongly with large ‘survival’ waves and should avoid the wave crest where velocities and accelerations are highest and least well understood. Devices do not need to pierce the water surface, although this is helpful for maintenance because divers are expensive, and economic designs may exploit this, using subsea intervention or variable buoyancy for access. Strong interaction with waves also affects towing, installation, access for maintenance and decommissioning.

2. Economics

In oil and gas, the marine structure, whether fixed or floating, is typically required to support weight and provide footprint/real estate with very high reliability. Robustness is critical because failures can cause hydrocarbon release, injury or fatality. Safety over-rides all other issues because the human and environmental consequences of failure are huge, in terms of both cost and reputation, compared with the cost of avoiding them. As part of a larger system, including wells and risers, accommodation and hydrocarbon processing (the payload) and export pipelines, the reliability of performance and schedule is paramount and cost to build, install, maintain and (eventually) decommission that marine structure, while significant, is of secondary importance. The schedule for fabrication and installation can also be critical, given the large initial revenues which pay for the rest of the system. Hence the marine component of offshore projects may be a small part of total project cost, while this is generally not the case in wave energy.

Consider a £6 MM gas platform (including piles and installation), which could be part of a £75 MM project, including wells, deck, process and local export pipeline. Initial production might be worth £1.5 MM per week gross; clearly a 15 per cent cost over-run on the £6 MM platform might be acceptable if it avoided a major hit to the schedule for the whole field. Even a week of delay in installation ‘costs’ £1.5 MM of production (or at least delays the field production curve by a week—but for the managers concerned, production in the year of installation may be a specified objective), so the designer will be willing to sacrifice some capital cost in exchange for greater certainty in installation schedule. Of course, there are substantial operating costs, tariffs to pay for onward transmission of gas to shore, and processing and entry tariffs. Production may decline fast, perhaps with a half-life as short as two or three years for gas; so the economics is not as spectacular as might be inferred. The business also has to support the exploration efforts that found the well, excluded from the figures above, as well as exploration efforts that found nothing. Offshore structure costs are driven up by these reliability and schedule requirements, while marine civil engineering (bridges, piers, etc.)
costs are lower. Wave power projects need to access this lower cost base, and project cost estimates should not use ‘offshore’ cost estimates without due care and attention.

In contrast, a £6MM wave energy device may be part of an £8MM system and will need to make perhaps £1.2 MM yr\(^{-1}\) (net) or £23\(\text{k}\) per week to pay for the capital cost. The developer will be much less concerned with schedule and much more focused on cost.

Costs for offshore structures may therefore be unrepresentative of what can be achieved in wave energy with a different approach to schedule, and ultimately mass production. However, if wave energy is competing with oil and gas for common resources, such as cranes, wave energy will pay the going rate, unless willing to sacrifice schedule for cost and ‘fit in’ to gaps in the suppliers’ workload.

3. Fabrication

Offshore structures are typically one-offs, built for different missions in different environments. Lessons learnt are transferred to subsequent projects but mass production benefits are realized only on repetitive components such as pipelines, drill pipe, flexible risers, etc.

Successful wave devices will be mass produced and there is potential for mass production savings, if devices are designed correctly. Design and fabrication contracts must incentivize cost reduction and allow the contractor to benefit from innovations that cut revenue. Fabrication contractors should be involved at an early stage of design to ensure that what is designed can be built cost-effectively. A Swedish semi-submersible drilling rig designer once remarked that its elegant and efficient structure was in part due to the design office’s proximity to the shipyard; welders would often drop in for full and frank discussions of hard to fabricate details.

Once devices are proved to be worth deploying in large numbers, it may be worth building specialized installation and maintenance vessels, as is happening in the wind power industry. Alternatively, devices may be designed for installation with the minimum of external assistance, but this may involve adding structure, such as buoyancy, which is only used during installation.

4. Offshore project design process

In summary, the design process breaks down into a few phases:

- Define requirements such as payload (processing equipment and accommodation, cranes, storage), riser numbers and support needs, desired deck area, helipad dimensions, etc.
- Define environment, including directional wave \(H_s\) and \(T_p\) combinations for 1, 100 and (depending on code) 10000 year conditions, for both summer (installation conditions) and winter seasons. Similarly, directional and seasonal wind and current will be defined, including persistence information for installation. Water depth (including tidal effects), seabed geo-technics and local seismic conditions are also specified.
Designers create and review a range of concepts that can resist the environment and achieve the desired performance; sometimes the design requirements are flexed to improve economics. Selected preferred concepts are outline-designed to meet the capability requirements, costed using simple metrics for materials (dollars per tonne) and equipment and project economics are evaluated. Often, lifetime economics will be calculated in a probabilistic format (using, say, Crystal Ball or @Risk), which not only creates probability distributions of cost and value but also determines sensitivity to uncertain inputs, helping designers to focus on the drivers of the most important uncertainties for further refinement. Usually, one concept will be clearly superior and will be selected for further development, with perhaps an alternative in reserve in case of unexpected developments, such as unavailability of required facilities. The design should consider all lifetime phases, i.e. fabrication, transport, installation, operation and decommissioning. Some of the early Norwegian gravity base structures have been deemed too large to decommission because there is no safe way to refloat the substructures, but wave energy designers cannot expect to be exempt from the requirement to decommission. Personnel from all disciplines need to be involved from the start; there should be no ‘over the fence’ design process where the designers do not consult the operations team but expect them to manage whatever they have been given.

The preferred concept is then optimized and designed in more detail, with manufacturers’ quotes for costs; if there are major surprises at this stage (e.g. no crane barge can meet the installation schedule), there may be a need to loop back and adjust the concept.

Once conceptual design is complete, the developer will solicit bids for the detailed design contract, subsequently selecting fabricators and installation contractors, then procure, construct, install and commission. Optionally, depending on the developers’ management capacity, an engineering, procure and construct contractor may be given responsibility for the process, typically with the developer’s staff integrated into the team.

Offshore developments usually use one-off designs for specific water depth, seabed conditions, environment, topsides weight and space requirements. In areas such as the shallow water southern North Sea or the Gulf of Mexico, designs may need only minor adjustments for deployment at similar sites. Lessons learned from each development are applied to subsequent projects, but true mass production benefits are seldom realized.

Project management is a vital part of the design and build process and is seen as a separate skill; great project managers are typically not designers or engineering problem solvers, and placing the wrong individual in the project manager role may have disastrous consequences.

5. What can go wrong?

The system must be designed as a system, for all life and include fabrication, towing, installation, operation and maintenance, and decommissioning. ‘Stovepipe’ teams (sometimes employed by different contractors in different
offices) who do not communicate can create problems for other parts of the project if they do not understand the implications of their design choices; interfaces need to be clearly understood and cost effects (e.g. substructure cost required to support incremental payload) made explicit. Design decisions can shift cost from one team to another; if this is the case, budget should move too.

It is tempting to focus on installed capital costs (capex) at the expense of operating costs (opex) or project value; designs must be assessed on overall economic return (discussed further below), otherwise capex may be reduced in a way that destroys value, perhaps by increasing operational costs or reducing production capacity.

Contracts should incentivize innovation to cut overall costs; for instance, an installation contractor usually has no incentive to suggest structural design changes that will cut costs if that innovation reduces its revenue. Alliance contracts set up a project target cost and reward all parties with a share of reductions—and penalize them with over-runs. These have been successful, but traditional contracts work well in most cases, particularly when detail design is finished before construction begins.

Risks can be ignored or misunderstood. The possibility of ‘gross errors’ in design is reduced by modern integrated loading and structural design software but can still occur. A robust checking procedure is needed to catch and remedy mistakes. A classic case is the sinking of the Sleipner ‘A’ substructure in 1991 during ballasting for the ‘floatover’ mating with the deck (http://en.wikipedia.org/wiki/Sleipner_A_offshore_platform). An error in finite-element analysis interpreted a resolved load as a total load, resulting in an under-designed wall section. While poor reinforcement detailing in the area was noted and revised, no one questioned the loading number. As the rig ballasted down, hydrostatic stresses exceeded the capacity of the wall, resulting in flooding of the column. The structure sank and imploded before hitting the seabed. Fortunately, no one was killed or injured but the commercial consequences were substantial.

‘Minor’ details may be critical, yet thought too ‘minor’ to be referred for engineering review. A tragic example (http://en.wikipedia.org/wiki/Alexander_L._Kielland_(platform)) is the small hole cut in one of the legs of the Alexander Kielland platform to allow the attachment of a hydrophone. The resulting stress concentration initiated a fatigue crack in a pontoon that failed catastrophically, capsizing the rig in an incident that claimed 123 lives in 1980.

The most onerous design conditions may not be identified, particularly for novel configurations. In particular, the largest waves may not be the most severe; inertia-driven loads are driven by wave height per period$^2$, and short period, moderate height waves can create the biggest loads.

Analysis may not evaluate extreme loads accurately. Survival waves can cause slamming loads that are hard to calculate (or may be ignored) or generate high-frequency loading that can excite structural resonances known as springing or ringing (not always represented in model tests for scaling reasons discussed below) well away from wave frequencies. A wave impact is thought to have broken a porthole in the ballast control room of the Ocean Ranger drill rig (http://en.wikipedia.org/wiki/Ocean_Ranger), initiating a series of events that culminated in the loss of control of the ballast system and rig capsize, resulting in the death of all 84 crew members in 1982.
Model testing is an established way to understand nonlinear loads and discover unexpected effects, such as the ringing and springing that were found to affect tension leg platforms and gravity base structures in the early 1990s. Combined directional loads depend on joint probabilities of wind, wave and current, and it is difficult to determine worst cases without extensive investigation. A floating production vessel may (for instance) be turned across the waves by wind or current, loading the mooring system more heavily than a unidirectional extreme weather case, and this is clearly a possibility for attenuator-type wave energy devices.

6. Big structures are weak

Survival is critical for both offshore structures and wave energy devices, and design for extreme seas is often a major driver of the overall system design. We do not intuitively appreciate the weakness of large items, and so ‘gross errors’ may be hard to identify; experience at human scale leads us to think that materials such as steel and cement are strong and rigid, while the reality is that large structures are rather delicate and flexible. Dimensional analysis illustrates this clearly. Water density is constant; so mass \( M \propto L^3 \), where \( L \) is scale. Gravity is constant; so \( T^2 \propto L \), where \( T \) denotes the time dimension. But elastic modulus \( E \) and yield stress \( \sigma_y \) have dimensions of force per area = \( MLT^{-2}/L^2 \), which, substituting for \( M \) and \( T \) in terms of \( L \), reduces to \( L \); so material strength and elasticity should be scaled as well as cross section to make big structures as rigid/strong as small ones. A strength-scaled model of a steel structure has to be made of the feeblest plastic.

Thus intuition is not a good guide to the dimensioning of big structures (at least for inexperienced engineers) and gross errors may not be obvious, as was the case for Sleipner ‘A’.

7. Wave and wind data

Wave data define both loading and energy production and also drive the design of installation and access procedures. The oil and gas industry owns large amounts of measured and hindcast data for large areas of UK waters. This provides statistics for wave conditions, based on 20+ years, hence the basis for structural design and load factor evaluation.

Persistence and predictability are also important for intermittent renewables such as wave energy, both for installation and access and for power valuation. Persistence modelling for wind and wave conditions appears not to be straightforward; while we can generate second by second time series of wind or waves consistent with a specified spectrum, there seems to be no rigorous route to generation of series of (say) three-hourly wind speeds, with appropriate seasonality and diurnal variation for the evaluation of weather-sensitive installation and maintenance operations. Are measured data the only safe option?

8. Reliability-based design

In oil and gas, reliability is critical; any structural failure will—at the very least—cause a shut in production, and may involve hydrocarbon release to the environment and, worse still, injury or loss of life.
Reliability-based design codes (load and resistance factor design) for marine systems, such as API RP-2A LRFD, ensure the desired level of safety for all failure modes. Traditional single factor-based design methods add loads of very different levels of uncertainty. For instance, hydrostatic loads are well understood, while, at the opposite extreme, wave impact loads are most uncertain; adding components with radically different variability into a single 100 or 10,000 year extreme figure is not rational. Reliability-based design methods factor loads before adding them together, using multipliers that are calibrated to give overall probabilities of failure that are acceptable and uniform across failure modes. This approach is designed to eliminate the need for probabilistic simulations of lifetime loads.

Risk-based design shows where to invest to get the best value by minimizing the overall probability of failure. For example, when the offshore business moved from a single load factor-based design approach to a reliability-based code, it became clear that too much resource had gone into making jacket substructures strong and not enough into making them tall. Any wave big enough to overload the jacket substructure would be tall enough to reach into the deck structure, creating huge forces not accounted for in the jacket loading analysis. A taller platform with less robust structure would be safer (and possibly more economical, although that is a side effect, not a factor in safety-related design decisions) than a structure designed under the old code.

Typically, the probability of failure of the structure is designed to be around $10^{-4}$ per annum, an order of magnitude less than the probability of failure in the crude and gas processing, which itself may be another order of magnitude safer than helicopter transport.

In wave energy, the marine structure is the business, not just a foundation for the business to stand on. Capital cost is critical; structural or mechanical failures only impact the device (unless it escapes to become a hazard to shipping), production loss is less critical to the economics, since the device is a much larger component of total cost, no hydrocarbons will be spilled and, in most cases, no personnel will be at risk. The wave energy system designer can cost optimize, balancing the expected cost due to failure of structure and components against the incremental capital and operational costs needed to reduce the probability of failure. Hence, wave power may ultimately use lower safety factors, because most failures will result in economic loss, not fatality, injury or hydrocarbon release. However, it is probably sensible to overdesign through the prototype phase, given the uncertainties and possibly the poor applicability of offshore codes to novel wave energy devices. Furthermore, reliability often increases steeply with cost; so a large loss of reliability may be entailed by a small cost saving and this needs to be well understood.

Reliability-based codes are better at analysing the structure as a system, but have been developed for ships as well as oil- and gas-type structures; so there may be room for risk-based design code development for novel wave energy devices.

9. Design optimization

Design optimization is critical, for all phases of a structure’s life, including fabrication, installation, operation and decommissioning.

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In 1979, Dyson [1] noted that there were no great nuclear reactor designs yet, and he would probably stand by this statement today; his rationale was that too few types (then about 100) had been built, whereas we have (for example) excellent motorcycles, because so many variations have been built, used and modified. Wave power is in a rather similar situation, with many device concepts under investigation and no agreement on the best approach. Optimization is equivalent to building and testing many devices and can lead to quite unexpected results.

The wave energy device designer ultimately wants to devise the most economically effective means to convert wave energy into power. Design improvement should not stop once the device can make money with (say) 5 renewable obligation credits (ROCs), because there are other wave energy devices—and other technologies—that need a lot less support than that. Governments will not indulge a high-cost technology for long. Climate change and energy security (and other calls on investment) are so serious that we cannot afford long-term support for ineffective technologies. Ultimately, wave energy must prove a cost-effective competitor with other low/no carbon options such as energy efficiency, wind, nuclear, carbon capture and storage, etc.—and the best of today’s devices seem to be on the way to that target.

Not all designers are entirely clear on what to optimize; should the target be minimum capex per installed kW, maximum efficiency, maximum load factor, lowest levelized cost of energy (LCoE) or what?

In fact, decision-makers do not care about any of these factors individually. They are looking to maximize capital efficiency, which is usually expressed as a (post-tax) dimensionless profitability index (PI; the number of times capex is repaid by discounted revenue) or internal rate of return (IRR)—the interest rate at which the project net present value would be zero.

Post-tax, post-financing economics can be very complex but, for ‘simple’ projects, it is straightforward to show, using dimensional analysis or basic algebra, that PI and IRR are monotonically related to net annual revenue per capex; so maximizing this value optimizes the PI and IRR of the project.

Both PI and IRR are dimensionless, annual revenue and opex have dimensions of dollars per year, while capex is expressed in dollars; the only way to eliminate the dollar signs in the analysis is to divide capex by annual (revenue – opex). Hence $\text{PI} = f(\text{capex}/(\text{revenue} – \text{opex}))$, where $f$ is some function of life, spend profile, tax...). The capex/(revenue – opex) figure is the payback period, the number of years of pre-tax revenue needed to pay back the capex. Not surprisingly, a little algebra shows that PI and IRR always get bigger (good) when payback period reduces.

Revenue is summed over the annual sea-state distribution (input energy $\times$ efficiency $\times$ load factor $\times$ net energy value). Operational expenses (opex) subtract directly from revenue (otherwise, owners could affect their returns by giving out opex with one hand while collecting it back as revenue with the other).

If we are developing a concept, and do not know the power price and hence the revenue, minimizing the LCoE is the correct approach, but, once the power price is known, maximizing capital efficiency is the objective that makes sense for the project developer.

Of course, a proper economist is required to decide whether post-tax economics is acceptable (particularly if the project is also financed with borrowed money), but that only happens once the design is as good as it can be, based on minimizing...
the simple payback. As a rough guide, capex/net annual revenue = simple payback less than 7 years typically yields acceptable returns. Some extremely long-lived projects, such as the hydroelectric power stations built in the UK to relieve unemployment in the 1930s and that are still working today, do not satisfy conventional measures of return but may still be worth pursuing.

Optimization ‘tests’ many different designs and can lead to unexpected solutions. However, it is difficult to wrap design and cost evaluation into a single algorithm for formal optimization processes such as genetic algorithms, which are very powerful and can handle discrete variables. Nonetheless, design iterations should focus on improving project PI and IRR, even if it cannot be shown that these metrics have reached a maximum by the time the project enters construction.

In the early stages of design, concepts can be compared using simple costing based on, for example, dollars per tonne of steel type metrics. It may be inappropriate to use economics to decide whether a concept is economically viable when it is poorly defined, but it is very useful to understand what would have to happen in terms of capex, opex, productivity, etc., for the concept to be economic.

Probabilistic economics, using distributions for uncertain costs and other variables, is very helpful in determining not only distributions of project value but also highlighting sensitivity to uncertainties and hence flagging up those areas most in need of better definition.

10. Not normally manned structures

Small structures in shallow water with little processing equipment, for instance gas platforms in the southern North Sea, are usually unmanned, except during maintenance. But, if people will ever be on a structure, it is not ‘unmanned’, just ‘not normally manned’. Such platforms are typically accessed by helicopter, while wave energy devices will usually be reached by boat for both practical and economic reasons. Lessons from the wind industry may well be helpful.

Designers must understand the economic consequences of unreliability and limited access, particularly in winter, when productivity is highest and the consequential cost of the downtime is at a maximum. Condition monitoring should drive maintenance; prediction of failure allows component replacement on routine visits and avoids knock-on failures as well as loss of production. Measurement and recording of device motions, loads, power conversion data, etc. permit prediction of failures, development of statistical models and design improvement for subsequent devices. Good communications, including real-time video, allow onshore expert involvement; this is very successful in reducing the numbers of personnel offshore, and eliminating the risk, delay and cost of transporting experts offshore.

Design for safe access is critical; safety is paramount and the Health and Safety Executive will not permit continued operation of unsafe systems. Transport time to site is included in shift length, which limits time on site and increases costs. Additionally, there are risks to transport and transfer from helicopters or rigid inflatable boats onto and from the device.
The electricity industry’s practice of physically locking off components that may not be used during a maintenance procedure ensures that miscommunication does not lead to tragedy; had the relevant Piper Alpha valves been padlocked shut, with keys held by responsible individuals, that disaster could not have happened.

Designers must minimize heavy component change and ensure that emergency accommodation is designed in and that evacuation for injured personnel is practical.

Once the wave energy devices are deployed at scale, there is an opportunity for specialist maintenance hardware such as remotely operated underwater vehicles for subsea operations or jigs for bearing replacement.

11. Wave project design

Different concepts may well fit different types of site (nearshore versus deepwater, steady long-crested swells versus shorter directional wind-driven seas). Site, resource, efficiency, load factor, power price, access, maintenance, capex, opex and transmission costs all drive the economics for a specified site.

In particular, there will be sites where transmission is a binding constraint until/unless a certain scale can be reached and/or the load factor exceeds a critical value or wave and wind transmission can share infrastructure; analogously, there are substantial gas resources west of Shetland, UK, that cannot be economically accessed, and some wave energy resources may fall into the same category.

Transmission dedicated to wave power will see a wave power-type load factor that can make it expensive per unit of energy transmitted. Designers should therefore optimize device and transmission jointly. A low load factor is expensive because that implies under-used capex, while a high load factor is also expensive at the device because ‘excess’ energy must be dumped frequently—but a high load factor does employ the transmission system effectively. Intermittency does cost money; how much depends on rules, transmission capacity and demand.

Storage is the ideal solution, either on the device or onshore near the start of the transmission, which can then be rated at average power, not maximum device capacity. Pumped hydro is not possible at all sites but has good round trip efficiency (and not all the wave power produced needs to go through the storage scheme) and capital cost can be moderate. Other technologies in development may rival pumped hydro in time. Some have proposed electrolysis to make hydrogen, but, if electricity is the desired final product, round trip efficiency is poor—electrolysers may be 80 per cent (higher heating value (HHV)) efficient but polymer electrolyte membrane (PEM) fuel cells are typically only 50 per cent HHV efficient (quoted efficiencies are usually lower heating value (LHV)), giving a round trip efficiency of 40 per cent, so the output power is 2.5 times the price of the input power, excluding additional costs for the electrolysers and fuel cell.

Wave power must compete with other options to create low CO2 electricity, or reduce electricity demand through energy efficiency. It is not at all green to spend a lot to achieve very little; some reject ‘conventional economics’ but it is critical to allocating resources to the most productive ways to cut emissions (so long as it includes all costs such as emissions)—the lower the cost, the more can be achieved.

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12. Wave energy: loading and structure

Many analysis methods carry over directly from offshore to wave energy; indeed, some of them, such as diffraction analysis for multiple floating bodies, were developed as part of wave energy research.

Well-understood areas include:

— hydrostatics;
— wave loading and dynamic response at first and second order;
— moorings/cables and mooring dynamics; and
— structures and fatigue.

Model testing is used extensively in wave energy and offshore, and test tanks are familiar with the demands of both applications. Scale model testing is often the only way to address some of the less well-understood areas such as large resonant motions of devices in moderate waves (which violates linearity assumptions) and response to large waves, including slamming and overtopping. The structural scaling laws mentioned earlier must be respected; resonant responses may need to be modelled by lumped or distributed compliance and the scaled compliance of air in oscillating water columns has to be modelled by additional air volumes.

The crest of the wave contains the biggest velocities and accelerations, hence it creates the largest loads and is the least well understood (hence these forces require the biggest safety factors, owing to their uncertainty); so designers should try to avoid putting structures in harm’s way. Large waves are almost irrelevant for efficiency and annual energy yield, but critical for survival.

Combined directional wind, wave and current can create onerous conditions. Understanding the joint statistics of the environmental parameters is critical, but identifying the most onerous conditions at the desired probability level, and determining the appropriate load factor, is difficult; the best approach may be to test in a variety of 1 : 10 000 combinations of directional wind, wave and current, with no factors on load and only a strength factor in the design check.

Design codes such as API RP-2A LRFD may not apply directly to novel structural forms because the partial safety factors in the codes may be calibrated to different structures/load statistics. An option is to use fundamental analysis to predict load and stress distributions; such probabilistic design is enabled by modern fast computing resources.

Economic wave power devices will be fabricated, installed and maintained in high volumes at sites with similar environmental and bathymetric conditions, and design optimization will be a much more important feature than in oil and gas.

13. Wave energy device design: problems

Some wave energy devices are based on a ‘good idea’, often for a component of the system, perhaps a motion to power conversion mechanism or perhaps a wave energy absorber. The objective is then to develop an economic system incorporating the ‘idea’.
Even if we are starting ‘in the middle’ of the design process, having developed and committed to some invention or component, the rest of the process can and should be executed rigorously to maximize the chances of success. The system needs to be designed as a system, taking account of interactions between components (e.g. hull, power conversion, installation and moorings/foundations) and activities (access and maintenance). There are many examples in all areas of engineering where, for example, lack of design for maintenance has had catastrophic consequences for operations cost—but saved some capital cost and no doubt earned the designer a bonus (or at least a pat on the back).

Understanding the potential $n$th device costs (in mass production) on the basis of prototype costs can be difficult. Clearly, there has to be a route to acceptable economics for a device to have any future; no government is going to commit the consumer to paying 5 ROCs per MWh for the power from several hundred kilometres of devices.

A design may be unacceptably expensive unless designed to be mass produced/mass installed and evaluation of these costs is important to make the case for long-term viability. Devices must be designed for inexpensive installation and maintenance; floating cranes are expensive unless they can be employed in an intensive campaign and save a great deal of cost somewhere else.

New components in wave power may be problematic. By analogy with wind turbine gearboxes (which look to the ignorant observer to be a pretty mature technology, yet continue to create problems), apparently well-understood components such as rotational and sliding bearings may not live as long as expected under novel loadings and in salty, wet environments. Design for ultra-reliability may be more cost-effective than design for maintenance or change out; hydraulics, for instance, is noted for its capacity to last in onerous service and hostile environments.

Power conversion and transmission equipment design can draw on offshore wind, and subsea oil experience and components may be common/mass produced.

14. Conclusions

Offshore and wave energy structures have very different missions and economics but the underlying science, engineering and commercial tools can be applied to wave energy. There is plenty of expertise in the offshore engineering contractor/consultant world, which must be applied in full awareness of very different system needs and economics.

System optimization to maximize capital efficiency is critical to the development of wave energy systems with competitive economics.

Finally, and most importantly, safety is crucial in both offshore and wave energy; it has to be designed into structures and systems, not bolted on afterwards.

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Reference