REVIEW

The lessons learned from the development of the wind energy industry that might be applied to marine industry renewables

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This paper considers the early experiences of the development of wind turbines and the wind energy industry in order to try and identify lessons learned that could now be applied to the developing marine renewables technology and industry. It considers both political and commercial incentives and engineering development.

Keywords: wind energy; lessons for marine renewables; commercial incentives; policy; technology development; history

1. Introduction

This discussion is predicated on the assumption that the wind energy industry has been a success, at least in its general outcome! Its journey to this position has been punctuated with many failures as well as successes, and hence there are plenty of lessons to be applied to new renewables technology. On a more parochial front, that characterization might well be disputed. Has wind energy been an industrial success for the UK or the USA? No! The USA is the world’s second biggest market after China, and yet almost all the turbines are imported; the UK has Europe’s largest raw wind energy resource—about 50% of the total European Union (EU) raw resource [1]—and yet almost all the turbines are imported. However, more wind energy was installed in both the USA and the EU in both 2008 and 2009 than any other source of electricity. That is surely a quite remarkable success.

The purpose of this paper is to try and apply those lessons to the new marine renewables (MR) industry, in general, and wave energy, in particular. The paper addresses development and support of new devices and does not consider market mechanisms except insofar as they had an effect on this subject.

The lessons learned are, by their very nature, historical and hence their application to MR may be anachronistic. Wind energy was (besides hydro) the first renewable source of energy to be commercially exploited. Its success has resulted in very early commercial interest in MR and necessarily colours the

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status of the MR technologies. Everyone is looking for the ‘next wind energy’!
The interest in MR both commercially and technically results from wind energy’s success. There has been significant technological progress in wind energy, most notably in computational tools, which has a definite impact on the interpretation of these lessons. Although there is much offshore wind activity now, and there is no doubt that lessons from it will be important, this paper ignores that fact and concentrates only on the ‘early days’ of wind.

2. Early history

The beginning of the present wind energy industry can be traced back to the late 1970s and early 1980s. There is, of course, a considerable history of wind energy for many hundreds, even thousands, of years before that point but, although relevant from a technical point of view, that activity is probably not relevant from a commercial/industrial point of view. For the purpose of this paper, the starting point is the late 1970s. As a brief cautionary tale for the wave energy industry, it is interesting to note that a couple of centuries ago, there were windmills, there were water mills, there were tidal mills and the Sun was used both directly and indirectly for all manner of purposes, but humanity has always tried to avoid rather than exploit the waves! Why is that? A key part of the answer is the ratio of working loads to extreme loads—in other words, survivability. At the same time, the energy resource contained in the waves is vast and hence well worth the challenge!

In cultural terms, the early days of wind were characterized by smocks and sandals, and a good measure of ideology. Are those same catalysts present in the MR industry? Are there enough hippies to make things happen?

(a) California and Denmark: market incentives for wind energy

There were two centres of strategically important activity in the early days: the USA and Denmark. The Carter administration in the USA introduced a set of tax incentives that encouraged private investors to fund wind energy development. The basis of those tax incentives was a payment per kilowatt installed and not per kilowatt hour generated. This tax incentive produced an enormous amount of activity, particularly in California, but the nature of the tax incentive resulted in the installation of poorly designed, low-quality turbines, many of which did not operate. The tax incentive, therefore, initiated strong commercial interest in the business, but produced unreliable and, in the long term, unfavourable results. It produced installed kilowatts, but did not generate kilowatt hours. In both countries, the typical size of turbines was 50–100 kW, with diameters being less than 15 m.

At the same time, there was small-scale activity in Denmark. This activity was largely due to Denmark’s reaction to its high reliance on imported energy during the ‘oil crisis’ of the late 1970s, which precipitated a move towards local electricity generation from indigenous supplies, including wind. This initial Danish engineering activity can best be characterized as ‘backyard or farmyard inventors’, and the fiscal mechanism used to encourage it was a combination of energy sales price and tax incentives. The early days in Denmark were
characterized by a groundswell of local support and local activity quite distinct from the much more centralized approach that is now generally in place to support renewables.

Some small industrial Danish companies notably from boat-building and the agricultural industry saw an opportunity to enter a new business and hence started to make wind turbines, initially for the domestic Danish market and later to supply the brand new, rapidly expanding Californian market. Among these players were Vestas, Bonus, Nordtank and Micon—all still active today in various guises.\(^1\) The vibrant Californian market encouraged these small Danish players to enter into an export market long before such activity would traditionally have been advisable. There were, of course, also American suppliers, one of whom could be argued to exist today: there is a legacy from US company US Windpower, which subsequently became Kenetech and, after a long journey through Enron Wind, became part of General Electric (GE). Its patents are still a matter of benefit and contention in the wind energy industry.

A picture similar to Denmark can be painted for Germany. An industry was created using an energy-based approach with a generous market incentive. It is safer to encourage megawatt hours than megawatts. In more recent times, the Chinese government has encouraged very rapid deployment of installed capacity, and huge quantities of turbines have been built, the availability of which is rather low. Some single installations in China known as wind power bases are planned between 3 and 10 GW—one 3.8 GW installation is presently under construction. There are, in principle, some 80 Chinese manufacturers of 1.5MW turbines and above. Recent government instructions have attempted to rationalize the Chinese industry and to move the emphasis to generation and away from installation. Capacity-based incentives are dangerous.

\((b)\) Capital grants—‘macho’ machines

In parallel to the small-scale development in Denmark, Germany and the USA, there was also much research, development and demonstration activity sponsored by large capital grants in Germany, the USA, the UK, Denmark, Sweden, Italy and The Netherlands. A summary of the players and their machines in development at the time is provided in table 1. A glance at this table reveals that none of the recipients of the substantial capital grants is still active in the wind energy manufacturing industry today. It also reveals that the recipients of these grants were predominantly large companies, often with an aerospace background.

The dominance of the aerospace industry resulted from a belief within government circles around the world that (i) wind energy technology was close to aerospace technology and (ii) if wind energy was ever to make a major contribution to energy needs, then very large turbines would be required. In (i) they were mistaken; in (ii) they were prescient, although the route to this end proved rather different from their expectations. The companies listed in table 1 were familiar with large capital projects funded by central government. Their interest in wind energy stemmed from this background rather than from any real belief in the future of the industry. Is this mistake being repeated in MR?

\(^1\)Bonus became Siemens Wind Power. Nordtank and Micon combined to NEG Micon, which was itself later acquired by Vestas.
Table 1. Global recipients of capital grants for wind energy in late 1970s to early 1980s.

<table>
<thead>
<tr>
<th>Country</th>
<th>still active in wind energy manufacture?</th>
<th>still active in wind energy?</th>
</tr>
</thead>
<tbody>
<tr>
<td>USA</td>
<td>Boeing no</td>
<td>no</td>
</tr>
<tr>
<td></td>
<td>GE yes, but no direct connection</td>
<td>yes</td>
</tr>
<tr>
<td></td>
<td>Hamilton Standard no</td>
<td>no</td>
</tr>
<tr>
<td>Germany</td>
<td>MBB no</td>
<td>no</td>
</tr>
<tr>
<td></td>
<td>MAN no</td>
<td>no</td>
</tr>
<tr>
<td>Sweden</td>
<td>Swedyard (Hamilton Standard) no</td>
<td>no</td>
</tr>
<tr>
<td></td>
<td>Kværner no</td>
<td>no</td>
</tr>
<tr>
<td>UK</td>
<td>British Aerospace no</td>
<td>no</td>
</tr>
<tr>
<td></td>
<td>Taylor Woodrow no</td>
<td>no</td>
</tr>
<tr>
<td></td>
<td>GEC no</td>
<td>no</td>
</tr>
<tr>
<td></td>
<td>Sir Robert McAlpine no</td>
<td>yes, in development</td>
</tr>
<tr>
<td></td>
<td>James Howden no</td>
<td>no</td>
</tr>
<tr>
<td>France</td>
<td>Ratier Figeac no</td>
<td>no</td>
</tr>
<tr>
<td>Italy</td>
<td>Aeritalia no</td>
<td>no</td>
</tr>
<tr>
<td></td>
<td>Finnmechanica no</td>
<td>no</td>
</tr>
<tr>
<td></td>
<td>Riva Calzoni no</td>
<td>no</td>
</tr>
<tr>
<td>Denmark</td>
<td>Elsam, Nibe A&amp;B no</td>
<td>yes, as a utility</td>
</tr>
</tbody>
</table>

Figure 1 attempts to summarize these two different strands of activity. In the figure, the grey-shaded turbines are placed approximately at the date when they became commercial. The so-called ‘macho’ turbines were developed as a result of large capital grants given to the companies listed in Table 1. In each case, the size of the turbine is approximately to scale. From this figure, it is clear that there was no connection between the turbines benefiting from large R&D funding and the turbines that were actively being deployed in the early commercial markets. The commercial turbines grew gradually and their size reached a plateau in approximately 1990–1995. At that point, there was a rapid increase in size that has continued until the present time. It is interesting to explore the reasons (i) for the plateau and (ii) for the later growth. The plateau at approximately 500 kW was reached essentially through the scaling up of commercial turbines, using rules of thumb and other pragmatic approaches to engineering design, often arising from government-sponsored efforts—especially Risø National Laboratory in Denmark (see §3). The manufacturers of these turbines did not have sophisticated design procedures and were understandably concerned about their ability to create larger and larger turbines. The ‘rules of thumb’ that they used served the early industry very well and were based on early work by Risø. At the bottom of the figure, the global capacity of wind energy is shown. When 400 kW turbines became commercial, there were already
1700 MW of capacity installed. At the stage in the wind industry equivalent to the present situation for MR, in terms of installed capacity, typical unit sizes for wind turbines were 10–20 kW.

Large capital grants applied to large companies familiar with government contracts will not start an industry.

(c) Wind Energie Grosse Anlagen (WEGA)

At approximately the same time, the European Commission (EC), through Directorate General DG12, seized an important initiative and encouraged all the main players to develop megawatt-scale turbines. The original motivation for the development of the macho machines shown in figure 1 was a conviction held among all of Europe’s utilities, and most governments, that wind energy could only make a significant contribution to Europe’s electricity needs if very large turbines were adopted. Ultimately, this conviction appears to have been correct, as can be seen from the right-hand side of figure 1, but the initial timing of the introduction of megawatt turbines was wrong—it was too early for the market. The same trend can perhaps be seen in the wave industry—there is a tendency to match the capacity of a wave energy converter to that of a typical wind turbine, a process that omits proper consideration of the characteristics of the resource. An EC programme known as WEGA was set up to provide exactly the same output (megawatt-scale turbines), but starting from a significantly different point. There were already 500 kW turbines in commercial operation, and the targets of the R&D funds were commercial entities with a clear interest in product development and not large corporations with an eye on public funds. It is simplistic to attribute the rapid development towards multi-megawatt turbines to the WEGA programme alone. There is, however, no doubt that WEGA did have a major impact—an important observation given the present considerations about
the way in which government intervention can have a material effect on MR. The scientific knowledge gained from macho machines was applied to the commercial development stream during the early 1990s and, hence, when commercial entities entered the WEGA programme, the result gave the industry both the incentive and the confidence to develop larger and larger turbines.

The WEGA project was not just about the development of the turbines, but also required measurement programmes to be adopted so that scientific lessons could be learned as well as commercial ones. It will be demonstrated later that full-scale, detailed structural measurements used to prove mathematical models have been vital to the rapid development of the wind industry.

An interesting psychological device was adopted by the EU to encourage participation in the WEGA project. Once initial interested parties had been identified, a large measure of peer pressure was used to ensure that others followed suit—a clear sign that a market era had been entered.

The coalescence of these two routes—the commercial route and the scientific route—was a vital milestone in the development of the wind energy industry.

Well-targeted R&D grants, including significant scientific content, used at the right stage of maturity can have marked effects.

**(d) What lessons can be learned from this dual track development?**

The big capital projects produced the macho machines and also engineering tools, and certainly improved the scientific understanding of the way in which wind turbines behaved. The understanding derives from a combination of computational modelling and careful structural measurement. The turbines also improved as a result of material testing and other component development. The reason why the wind business has been able to develop so rapidly and to produce the present giant turbines is the potent combination of mathematical modelling and testing, combined with the development of standards and certification agency rules. There was considerable foresight demonstrated in the macho programmes, particularly in Europe, which included very advanced measurement campaigns. These campaigns were not limited to simple performance measurement (power versus wind speed curves), but deployed dozens of sensors able to measure the dynamic response of the turbines and hence validate the mathematical models. The absence of such a comprehensive approach in MR is clear and is an important missed opportunity. This matter is discussed further in §6c. In retrospect, it is quite clear that, had the scientific capital that was aimed at megawatt-scale development in the 1980s and early 1990s been invested directly in commercial-scale turbines, which, at that time, were at a scale of 100 kW or so, then the development would have been much more rapid. But how could that have been achieved?

None of the early recipients of substantial capital grants is now present in the manufacturing business, but many of the people who were involved in that development are now present in other spheres of wind energy activity and hence the science lives on in other commercial entities. Wind energy has proved to be addictive in nature and, despite the demise of many organizations over the last three decades, most of the pioneering engineers are still actively employed. Although, superficially, the legacy of the macho programmes and the early commercial companies may not be visible, it is extremely strong and has been important in the industry’s development.
3. Institutional investments

(a) Central test sites

Some scientific infrastructure was put in place in several different countries in order to provide a central source of testing and engineering expertise. Most notable of these were the Risø National Laboratory in Denmark, the Energieonderzoek Centrum Nederland (ECN) at Petten, the National Engineering Laboratory (NEL) in East Kilbride in Scotland, the National Renewable Energy Laboratory (NREL) in Golden, Colorado, and various test sites in Germany. All continue to this day. The European Marine Energy Centre (EMEC) test site in Orkney, Scotland is a pioneer for MR, and Wave Hub in the southwest of England may also play a part. To be effective, these establishments must provide scientific staff as well as physical facilities.

(i) National Renewable Energy Laboratory (NREL)

NREL has benefited from what, in European terms at least, appear to be substantial funds from the US Department of Energy. The US industry has suffered from sporadic market support; having been a very important global player in the 1980s, it became dormant for approximately a decade after the end of the Carter administration. The absence of any real influence by NREL on the industry either domestically or globally may, therefore, have more to do with the sporadic nature of the production tax credit (PTC) support than its own local activities. NREL continues to be the scientific focus for American activities and, under the Obama administration, is likely to remain important. If the US industry becomes more firmly established with real American roots, initially through GE, then its role may change; for the last three decades, it has remained one fixed point in a turbulent environment.

(ii) Energieonderzoek Centrum Nederland (ECN)

The ECN test site at Petten is, like NREL and Risø, based on a nuclear research site. ECN has been, and continues to be, the centre for much high-quality wind research, but there is now a singular absence of any commercial activity from Dutch manufacturers. In earlier days, in the 1980s and early 1990s, when Dutch manufacturers were active in the field, there was good contact and much communication between the manufacturers and ECN, and collaborative research projects were common. The reason for the Dutch manufacturing failure, therefore, appears to have been as a result of limited geographical space and poorly defined market incentives rather than a lack of centralized technical knowledge. ECN remains very active in the wind and the more general renewable energy market.

(iii) German test centres

WINDTEST Kaiser Wilhelm Koog and WINDTEST Grevenbroich were originally set up by a combination of Germanischer Lloyd (GL), local government and local utilities to encourage testing and employment around the new wind energy industry. Neither of these establishments undertakes direct R&D for companies, but both continue to provide independent testing. WINDTEST KWK is now part of GL Garrad Hassan and hence part of the GL Group, which is
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also engaged in certification. A similar role has been played by the Deutsches Windenergie Institut (DEWI) and its test site in Wilhelmshaven, which was established by the state of Lower Saxony to provide local employment and expert advice. These institutions have also played important supporting parts in the development of the German industry but have not had the ‘industry nursing’ role of Risø in Denmark. Minor roles were also played by the Wind Consult test site in Burgeshagen and the inland site on the Vogelsburg used by the Institut für Solare Energieversorgungstechnik (ISET).

(iv) National Engineering Laboratory (NEL)

The NEL test site at East Kilbride was set up close to the NEL, which was one of the UK’s central engineering laboratories with expertise in many engineering fields. In principle, therefore, it should have been a very good vehicle for the introduction of the latest engineering techniques into this developing industry. However, it became active in 1983, but did not attract its first turbine for some 5 years. Latterly, NEL has been acquired by Technischer Überwachungsverein (TÜV) and after an absence of some years has returned to the wind energy industry, mainly as a testing agency for small turbines. The British wind energy industry has not prospered and in the large-scale activities neither has NEL. The author understands that NEL was actively involved in the wave energy programme for the UK in the 1980s, which produced important basic data and mathematical models that have been applied in the industry.

(v) Risø National Laboratory

The most successful test site when considering basic research and general industry support is the Risø test site at the Danish National Laboratory. This site was originally called ‘The test site for small windmills’ and its very name is important in determining why it was successful. The early wind energy activities in Denmark were characteristic of the national Danish attitude towards business and the environment. The Danes and, indeed, the Germans have considered energy and the environment as important parts of their political agenda for much longer than the rest of Europe. The type of debate that is now in progress in the UK has long been a part of everyday conversation in Denmark. There was, therefore, a natural climate of cooperation and encouragement within Danish society, and there was government support for the small manufacturers to collaborate with the scientific institutions. The rationale for the Risø test site was to provide a hospitable location for small players to demonstrate and test their turbines. From the very beginning, scientific measurements were made on these turbines using Risø staff. Measurements were made of the wind and on the turbines. Access to this type of scientific staff would clearly not have been possible for a small ‘backyard’ manufacturer. No capital grants were given to these small manufacturers. Their incentive for entering the market was to earn money through the market mechanism itself. Much of the engineering knowledge and technical output was pooled.

In addition to the manufacturer support and testing activity, the scientific activity at Risø and also more fundamental work at both Risø and the Technical University of Denmark (DTU), there was also some large-scale activity along lines similar to that undertaken in other European countries, which was coordinated.
by the two Danish utilities Elsam and Elkraft. In the early days, the Danish Energy Agency funded the construction of two prototype turbines specifically designed for scientific investigation. These were not commercial machines. They were constructed at Nibe and were operated and supervised by staff from the DTU. They used two different types of configuration: pitch and stall regulation—two very different types of design approach. The data were measured, analysed and published freely. Another larger machine was erected by Elsam at a later date.

Risø may be considered as the collective R&D department for the plethora of small Danish wind turbine manufacturers. They were able to rely on Risø to help with technical and testing problems. In recent years, Risø forged closer relations with the major manufacturers Vestas and Siemens as well as the certification agency Det Norske Veritas (DNV). Risø has now become part of the DTU. Risø played a vital role in the development of the early wind energy industry, and this role deserves careful consideration in the development of the MR industry. Technical needs are similar, but the cultural and commercial circumstances are substantially different; if commercial conditions now allow it, a similar institute would be useful for MR.

Risø’s success was due to its carefully targeted remit, the positive commercial/political backdrop and knowledge sharing.

(vi) Spanish test centres

Spain did not participate strongly in the early development of the wind industry and hence its present highly visible position in terms of both national market and industry is particularly remarkable. It did, however, establish the Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT) government facility, which played a supporting role. There was a strong emphasis on first national and then regional benefit. Centro Nacional de Energías Renovables (CENER), the national renewable research centre, is a product of the approach and, while it cannot be considered to have played a global role in the early development of the industry, like NREL or Risø, it has demonstrated a possible role for a regional scientific establishment. Like NREL, its remit is renewable energy in general.

(b) Standards and certification

Early in Risø’s activity, the importance of standards and norms was recognized and systematic measurements were made of the inflow conditions into the turbines and their performance: load, power, noise and, later, power quality were habitually measured. This activity was the beginning of the establishment of the certification process in Denmark, mainly through DNV, and similar activity was under way in Germany with GL and the state of Schleswig-Holstein.

In order to obtain benefit from the market structure that was introduced into Denmark, it was necessary for the turbines to carry a certificate. In the early days, these certificates were rudimentary, but the requirement for them laid the foundations for important regulation and improvement of the design and construction quality. Despite these early standards, there were, of course, many failures of almost all components, the most common being blades and gearboxes. Failures, often of a substantial nature, were commonplace in the wind energy
industry at this time, and should be expected as part of the natural development
of a new technology. Expectations of the short-term performance of new MR
devices should be tempered by this realization.

Failures were commonplace and the same will happen in MR.

The role of the classification societies, in particular GL in Germany and DNV in
Denmark (although its ‘home’ is Norway), has been crucial. They have acted
in competition with one another and also in concert with the national and
international standards agencies to provide sets of rules and design appraisals
for the wind turbine industry. A more nebulous, but nevertheless crucial, role
has been as a central ‘repository’ of knowledge and experience. The development
of the standards and rules and their application to wind turbines have allowed
owners and lenders to gain confidence in the turbine designs.

A certificate from a classification society does not provide any insurance of
the product. It simply represents evidence that a third party has appraised that
design. It is not a certificate of reliability or availability; it is primarily a certificate
that addresses matters of safety. The role and the validity of certificates are
commonly misunderstood.

Other classification societies have also been involved tangentially: Lloyd’s
Register in London, Bureau Veritas in France, Underwriters’ Laboratory (UL)
in the USA and TÜV in Germany have all played minor parts. TÜV and DEWI
Offshore and Certification Centre (OCC) are now quite active.

GL has regularly published extremely comprehensive guidelines for wind
turbines [2]. The detail and effort involved in the development of these ‘rules’—
which, in concept, are based on standard practice in the maritime, oil and gas
as well as wind energy industries—are substantial and they are used by most
certification agencies for the provision of certificates. A similar approach has been
adopted jointly by DNV and Risø.

In parallel to the development of certification rules, comprehensive standards
have been developed under the aegis of the International Electrotechnical
Committee (IEC). There is now a series of standards known as IEC 61400 [3]
that cover many aspects of wind turbine design, safety and measurement. This
series is a cornerstone of the wind energy industry and has taken several decades
and several centuries of professional resource to develop.

The MR must strive for similar internationally accepted standards and
certification rules and, indeed, this process has started with the creation of the
IEC Technical Committee 114 known as TC 114 [4], which is tasked with the
preparation of international standards for marine energy conversion systems.

(c) Certification: reassurance or constraint?

The action of the certification bodies and the influence of standards have
clearly been valuable in improving quality and removing common faults. However,
the development of rules and standards does also have a constraining effect
on the development of technology, and there is a very delicate balance to strike
so that, on the one hand, benefits accrue from the development and application
of high standards and, on the other hand, creativity of the engineering designers
is not constrained.

Superficially, wind turbines now all look very similar, with three-bladed upwind
rotors, with variable pitch and variable speed, but it is important to recognize

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that, in the early days, the variation was enormous, very similar to that presently seen in MR. There is now a superficially generic type of turbine, which does, of course, ease the development and application of standards—a fairly uniform means of load definition and computational modelling can be developed and applied. A similar type of consensus is present in tidal stream devices and, indeed, the consensus may be closer now in that discipline than it was in wind energy some 15 or 20 years ago. The same is not true of wave devices—each device has very different characteristics and it is hard to see what generic design tools could be developed to be applied to all of them. The challenge for the development of standards for wave devices is, therefore, substantially larger than that for tidal stream devices. There may be a tendency to collect together a compendium of possible relevant rules and standards from other related industries. This approach is unlikely to be helpful and will tend to constrain rather than aid development. Perhaps redefinition of the concept of a type certificate for a class of wave energy converters is needed (point absorber, alternator, terminator or bottom-mounted and floating), which would be applicable now but be adaptable for the future should a particular class be successful.

A balance between reassurance and constraint through certification and standards is vital.

Quite apart from the importance that standards have displayed in safety and design, they have also played an influential part in the commercial and contractual implementation of major projects. Formal performance tests and environmental compliance are always demonstrated through IEC test procedures. Maturity and hence ‘financeability’ of designs always rely on the provision of certificates from recognized certification bodies.

Mature standards and formal certification will be vital ingredients of a commercial MR industry. They will be prerequisites for financing significant projects.

\( (d) \) The legacy

The certification bodies continue to play an important role in assuring quality, but the test centres are now less appropriate as centres to apply technology directly within industry, i.e. providing the technology needed to make the present generation of turbines work. Their role is now (i) to provide locations for easy erection of large-scale test turbines with a minimum of bureaucracy and (ii) to provide technological tools for future, long-term development. They are turning their attention away from focused turbine development and more towards the generic requirements of the industry—understanding the wind as well as understanding offshore activities and new materials. There is a general recognition of the importance of grid integration and that is receiving considerable attention. This activity will provide information and experience directly relevant to the MR industry.

4. British experience

This paper is destined, initially at least, for a British audience and hence a brief deviation from the global commentary to a national one will now be made. The British industrial experience of wind energy has not been a happy one.
In discussion of MR, the history of wind energy is often identified as the model that should not be followed. It is certainly true that there is no manufacturer of wind turbines in the UK. Until very recently, there was a large wind turbine blade plant run by Vestas whose technical lineage could be traced right back to the early British industry pioneering days of the late 1970s. Sadly, that has now closed. The recent upturn in the UK market has seen plans for manufacture under license of various major manufacturers. This outcome is certainly positive but is surely a pale imitation of what could or even should have happened, given the UK’s wealth of raw wind resource. The reasons for this failure are often not properly understood and some detail is provided shortly because this may be relevant in the context of MR.

The Department of Energy (DoEn)—this department had responsibility for energy in the 1970s—support for the nascent wind energy industry was generous. It took the form of substantial capital grants to three major recipients: the Wind Energy Group (WEG), which consisted of Taylor Woodrow Construction, British Aerospace and General Electric Company; James Howden; and Renewable Energy Systems (RES), which is a subsidiary of Sir Robert McAlpine. WEG and Howden concentrated on horizontal axis turbines, subsequently adopted as the norm, and RES concentrated on vertical axis turbines, which are no longer considered commercially viable.

In 1986, WEG produced the MS2 (a three-bladed, pitch-controlled, 200 kW, 25 m diameter turbine), which, at the time, can be considered to have been directly comparable to the equivalent Vestas turbine that was then in commercial production (Vestas V27, 225 kW, 27 m diameter, three-bladed, upwind, pitch control). WEG consisted of three very substantial companies, none of whose existence depended on the success of their turbine in a commercial sense. They were recipients of substantial sums of government money and, as long as that government money continued to flow, WEG was happy to continue with its wind energy activity. It was primarily a research organization and it produced five substantially different turbines: LS1, 60 m; MS1, 20 m; MS2, 25 m; MS3, 30 m; and MS4, 600 kW, 40 m. The MS2 turbine was a direct and very credible competitor for the equivalent Vestas turbine at the time. WEG benefited from dynamic leadership at this point, and the Danish (Vestas) and British (WEG) technologies were directly comparable. The MS3 and MS4 were driven more by technical optimization than by market forces. The MS2 was a direct market competitor.

As part of this development process, WEG produced a lot of useful science—computational codes that started to provide accurate prediction of loads and detailed measurements of the structural dynamics of the turbines. It also benefited from significant generic university R&D activity such as materials testing. No decision was made by the DoEn to concentrate academic funding for wind energy R&D in any particular institution and hence no ‘centre of excellence’ was established. The result was that expertise was transient and hence in the long term of little use. A different approach was taken in The Netherlands, Germany and Denmark, where Delft, Stuttgart and DTU, and Risø remain useful resources to this day.

A limited number of centres of excellence should be established in universities.

At a crucial time, when WEG was developing turbines for application in commercial wind farms, the UK market mechanism was the Non-Fossil Fuel Obligation (NFFO). The NFFO approach provided a competitive market into
which renewable energy projects could bid. The result was very low energy prices, probably the lowest seen anywhere in the world, and projects developed on very high wind speed sites that, by their very nature, attract the maximum environmental opposition. The latter characteristic was ultimately the reason for NFFO's demise. The only positive attribute of the NFFO was its use of technology bands that prevented less mature technologies from having to compete with more mature alternatives. This approach did allow parallel development of different devices.

Separate markets should be developed for technologies of different maturity.

The competitive nature of the system was an opportunity for manufacturers from abroad, in particular from Denmark. The NFFO was conceived at the height of the Thatcher government and, hence, competition was sacrosanct—there was no sense of protectionism such as has been seen in other markets, for example, Denmark, Germany and Spain. The Danes were able to produce slightly cheaper turbines than WEG and hence benefited from a majority share of the potential NFFO market. In addition to this hot competition, some serious accidents occurred at a crucial moment when major developers were deciding upon which turbines to use for their projects. Overnight, this event cut the ground from under WEG's feet. A different market structure with less emphasis placed on competition and slightly different timing would have allowed WEG to stay in the market. Some form of support for national manufacturers was needed—every other country had one!

James Howden was the recipient of much smaller capital grants than WEG. Howden was a medium-sized manufacturing company familiar with the development of rotating machinery. It had a few prototypes operating in the UK, and its first major commercial development was in the Altamont Pass in the USA. Like many other manufacturers at the time, the Howden turbines suffered from a serious problem with their blades, and the entire wind farm was re-bladed at Howden's costs. The US industry was very favourably surprised to witness a company supporting its product in this way. The normal American approach at that time was simply to dissolve the company and to start again with no liabilities. Shortly after the re-blading exercise in the Altamont, there was a change of management at Howden and the new arrivals were circumspect about the industry's future. In addition, there was no substantial market between the Californian boom of 1985–86 and the early 1990s. A combination of circumstances, including the change of management, led to the demise of Howden's turbine manufacturing. Howden built a 26 MW wind farm of 300 kW machines in the USA—one of the biggest projects in the world at the time. It ran for over 20 years (its design life) albeit with significant maintenance. Had matters been decided differently, Howden could have been a very strong competitor in the global wind industry now.

RES was in a mould similar to WEG. It received considerable capital grants and, although RES is still active in the business, it is now active as a world leading developer rather than as a manufacturer. RES decided to develop vertical axis turbines, which, at the time, were considered to be viable competition to horizontal axis wind turbines. Experience showed that, at least at small to medium size, the vertical axis solution was not viable and, hence, however the money had been used, the RES developments through their company at that time, Vertical Axis Wind Turbine (VAWT), were probably doomed. This
experience, along with similar experience with other manufacturers of vertical axis wind turbines, may be considered to be a natural part of the evolution of the technology. RES also produced a prototype horizontal axis 1 MW turbine that operated successfully but was not pursued commercially. The absence of VAWT as a present-day manufacturer cannot be laid at the door of the way in which the development was funded—it is a matter of physics. It should, however, be noted that new proponents of vertical axis wind turbines are now emerging for use at very large scale.

The purpose of this extended description of the UK experience is to demonstrate that, in the case of WEG and of Howden, there were unusual circumstances, both of which were precipitated by significant accidents that caused the downturn in activity and subsequent withdrawal of each company. Both companies were producing turbines that were comparable to the international competition. The complicated nature of the WEG company and the size of its partners made it difficult to move quickly and decisively. Howden was freer and in the long term, probably better suited. Neither company benefited from a ‘soft’ domestic market. There was no chance of any protectionism during the Thatcher era, which would have allowed a British business to develop in the face of stiffer competition from outside. In RES’s case, the vertical axis technology was simply inferior to the competition, both domestic and foreign.

Failures must be expected. Some technology development will fail as a result of its natural inferiority. Business decisions may be taken for short-term, non-strategic reasons that will nevertheless affect the long-term strategy.

As mentioned earlier in a global context, the legacy of all of these companies lives on, in RES’s case very clearly with the same people in the same company under the same ownership but doing a different job. For WEG and Howden personnel, the commercial and legal framework has changed but the experience and expertise lives on and has formed the backbone of the existing UK wind activity.

5. Late entry

Some investigation of the right time to enter a new market is instructive. One of the most successful countries, in terms of both industrial activity and installed capacity, is Spain. There was very little activity in Spain during the early days of wind energy development. Wind energy development essentially started in Spain with a Royal Decree that was published in 1994. In a way similar to that used by the German government, a clear statement was made to potential Spanish owners that a high degree of local ownership would be required in order for them to obtain building permits. The result is that Spain is now Europe’s largest market. The Spanish industry now boasts the fourth largest global producer in the form of Gamesa, which is exporting all around the world. There has been no central government R&D expenditure on Gamesa, and their entry, as well as that of other smaller Spanish participants, has been entirely dependent on the strength of the Spanish market incentive system.

A very similar story can be told for India. India is the fifth biggest market and, through a structure of import taxes, it has only been possible to participate in the Indian market through a large amount of local manufacture. Using a high
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degree of business acumen and taking advantage of all opportunities that were offered to them, the Indian company Suzlon has now appeared on the world stage of wind energy in a prominent fashion. It is now at number six in the manufacturers’ table, from which it was completely absent even 5 years ago. There are other examples of successful late entry, although none as impressive as that of Suzlon.

The most marked late arrivals are to be found in the Far East—in Korea and China. The Chinese experience—the largest market with the largest number of manufacturers—is difficult to translate into European terms, because its development is based on a very different culture and a very different economic model. There is, however, one lesson for MR—if the Chinese see the potential for a new technology, they will enter in a forthright manner. There will be a large domestic market and, later on, the export market will be explored. The major threat for the dominant European wind turbine manufacturers is now Korea. Household names with huge manufacturing and engineering capability are entering the business with speed and investment difficult for the incumbents to match. They are aiming not at any initial domestic market but at export. They will be major players within the next few years. Given Korea’s major shipbuilding interests, we may expect to see a similar approach to MR, if they perceive that the market is significant enough.

6. How was cost reduction achieved?

Figure 2 shows the change in capital price per kilowatt of the Bonus range of wind turbines. Bonus was bought by Siemens and is distinguished by being the only major Danish manufacturer that has been active for the long term without being bankrupt. This graph may, therefore, be considered as a rather simple representation of the way in which the industry’s costs have fallen with time. The real costs may have been different, because—for large projects—they will be a matter of negotiation. It stops in 2005 because, at that time, major commercial changes took place in the industry, which resulted in a quantum leap in price. This graph begs the question of the reasons for the reduction in cost—is the reduction due to improving technology, to increasing volume or to increasing turbine size? The answer is, of course, that it is due to all three acting in parallel, but it is the author’s conviction that the main pressure on cost came from volume. Unrealistic expectations are often projected for new technology as a result of innovation. Volume is the dominant factor!

Cost reduction comes primarily from volume.

(a) Survival is the key

There are four phases in the development of a new turbine: conception, prototype, zero series and volume production. The same phases apply to the industry as a whole. In the early 1980s, the wind energy industry was in the prototyping stage. Although the number of turbines in the field was substantial, running into several thousand in the USA, all suffered from problems that are commonly associated with prototypes. The main task of the industry during this phase was simply to make the turbines work and survive. No real attention was paid to cost reduction, aesthetics, efficiency or power performance improvement.

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One characteristic of renewable energy that applies both to wave and to wind energy is that the devices are subject to large, ill-defined natural forces. At least some elements of the tidal loads are well defined and bounded. In the early days of wind energy, it was quite clear that these forces and their interaction with the turbines were not properly understood. Many surprises resulted, which, in turn, caused failures. Understanding the reasons for these accidents, and therefore preventing them, is a challenging task on its own and one that is clearly encountered near the beginning of a technology’s evolution. The author considers that MR is just entering this phase. Any real attempt at cost reduction is therefore premature. The main aim must be to allow the devices to survive in the physical environment that will be experienced on commercial sites. Few, if any, MR devices have yet been subjected to real survival conditions and yet several have failed.

The main aim of any incentive or investment system in MR at present must be to help the devices to survive.

Given the relative commercial maturity of the wind industry, unrealistic expectations are being made for MR devices. The MR industry closely resembles the wind industry 15–20 years ago. Figure 3 shows some photographs of wind turbines that were commercially available in the late 1980s. The variety of designs is clear. None of these design approaches survives today. The modern ‘consensus configuration’ is not shown. It takes a lot of work to identify the optimum configuration, although, in the author’s opinion, it may just be that the optimum design is the design on which most optimization effort is spent—the reciprocating internal combustion engine is a good example of this principle! Some lessons from the wind industry should be learned and, given the strong commercial interest in all renewables, perhaps this time scale can be accelerated, but a proper context should be retained. MR, in general, and wave energy, in particular, are in the survival rather than in the efficiency stage. This statement does not imply that cost-effectiveness and efficiency are unimportant—they are vital, but secondary at present.

After prototypes, the main aim is survival alone.
Once the behaviour of the devices has been understood, measured and modelled, then optimization of the devices can begin. Initial failures, which will occur, will help to form the standards and norms and will focus the attention of engineers on the sensitive parts of the structure, thereby improving them. A key strength of the wind energy industry was the parallel development of measurement campaigns and computational models. These activities were performed both on a national basis in several different countries and also on a broad scale within the European Community (as it was then!). Several so-called benchmark exercises were instituted by the European Commission and their benefit was widespread. The work consisted of detailed measurements being made on one, or several, research machines—typically these were machines that had been funded by domestic governments. These measurements were pooled and various different entities were involved in predicting the behaviour of the turbine. A general comparison with the measured results was then undertaken. Fatigue and extreme loads were measured and predicted, as was power performance. These tasks were performed in a spirit of cooperation and collaboration.

It is impossible to over-estimate the importance of high-quality, well-validated mathematical models. The wind energy industry can now justifiably claim to have ‘virtual turbines’. The MR industry must strive for this same goal. Many fascinating problems appeared in the wind industry:

— the strong coupling between the different components of the turbine, the control system, rotor, tower and drive train, etc., all affect one another;
— the combination of deterministic and stochastic loads;
— the extremely large number of cycles that materials must survive; and
— proper understanding of the inflow conditions.

Some of these will be shared with the MR industry, but there will be plenty of new challenges.
Validated, comprehensive mathematical models are absolutely essential.

Figure 4 shows an early experiment that was undertaken to investigate the behaviour of wind turbine wakes and used as fundamental data for the development of wake models. Figure 5 shows the level of agreement between modern models and measured data. A direct analogy can be drawn between the early wind work and the very substantial PerAWaT project [6], which is now in progress for MR, together with wave and towing tank experiments. In wind energy, there was relatively little use made of physical model testing. For MR, this approach has already been added to the general list of modelling techniques and is indeed being applied in PerAWaT.

(c) Investment too early: knowledge sharing

A key difference between the present MR activity and the old wind energy activities is the premature commercial environment that now seems to prevail in MR. As a result of the commercial success of the wind energy industry, many venture capital companies have made investments in the young MR industry, resulting in a high level of secrecy. The level of investment provided by these venture capital funds is relatively modest, but the secrecy requirements accompanying them are onerous. The result of this combination is that the individual device developers are under-funded with respect to necessary research and development, and are prevented from sharing their problems and solutions with one another. Consequently, many common mistakes will be made by each of the device developers separately, with no benefit in knowledge sharing or aggregation.

This condition was not experienced by the wind energy industry in the early days. There is no benefit in being nostalgic about the naïve days of early wind energy development, but there is, perhaps, some value in determining whether some of the benefits of knowledge sharing and joint research can be rescued from the prematurely commercial conditions in which MR is attempting to develop. Serious thought should be given to determine whether there are generic vehicles that could be developed, either computational or physical, in which the
Figure 5. Early wake model predictions and measured velocity profile results for a single turbine [5], at positions (a) 2.5 diameters, (b) 5 diameters and (c) 7.5 diameters downstream: free-stream boundary layer (red, dashed); eddy viscosity model (black, solid); wind tunnel measurements (blue, dotted) (Online version in colour.)

Various participants could share. Drawing from the wind energy industry, possible examples are:

- turbines that were purchased by some central agency and made available to researchers;
- the identification of generic research activities that would help all players, for example, blade fatigue and extreme load testing;
- characterization of the wind and wind flow models;
- materials testing for new materials, such as wood epoxy, glass epoxy and glass polyester; and
- development of industry standards.

Some careful thought is needed to determine how close a parallel can be drawn between the present circumstances for MR and the situation that prevailed two and a half decades ago for wind. There is now strong commercial interest in renewables from financial investors and utilities that simply did not exist in the early days of wind. Perhaps, a necessary cost of the commercial interest is secrecy, but it will certainly hinder technical development.

7. Conclusions

This section attempts to collect together in a summary form the various lessons learned by the wind industry that could be of use to MR. This summary has been produced with the UK industry in mind.

- Large capital grants alone do not produce a successful industry. Starting small and growing organically is likely to be more successful.
Market incentives alone based on energy produced, provided they are sufficiently generous, will provide a viable industry in due course, provided that the technology is not itself flawed and provided that fundamentally different technologies are not made to compete. Leaving technology development entirely to a market route is, however, likely to be slower than necessary.

Finding the right combination of scientific endeavour and commercial imperative is the key.

Very large companies may well not be the right vehicles for early development of MR devices.

It must be expected that some classes of device will prove either uneconomic or simply incapable of resisting the external forces.

A generous, protected market in the UK will be the single most powerful means of encouraging both a UK industry and a large UK installed capacity.

Understanding the harsh environment in which MR devices work and being able to predict their response to it and the resulting lifetime with confidence will provide the foundation for the development of a successful industry in the future. The absence of any such calculations and measurements spells disaster or, at least, long dangerous delays. Performance and efficiency do, of course, still remain a vital part of the process alongside extreme and fatigue loads.

There will be serious failures. The MR technology is still at a very early stage of development and the main aim for the present must be simply to make the devices survive in the sea. Any thought of cost optimization is inappropriate at this stage. A requirement should be placed on recipients of substantial sums from a market stimulation programme or some other fiscal instrument to make measurements and, as far as possible, to share those measurements.

Work should be put in to the development of generic modelling techniques for individual devices and for the characterization of the resource and external loads. Arrays of devices must also be modelled.

Standards and certification approaches should be developed. Initially, they should concentrate on energy evaluation and move on to safety and structural evaluation. Care should be taken to make sure that any certification rules do not constrain the engineering development of new devices.

It should not be expected that MR devices will be able to compete directly with wind in the foreseeable future.

Expectation of the performance of the first devices to be deployed should not be over-optimistic. Survival should be considered success.

Encouragement should be given to industrial investors in the devices who are able to take a long-term engineering view rather than the short-term financial view typical of venture capital institutions.

As for wind energy, the raw resource for wave energy is simply vast and is not a limitation for the industry.

High-quality, well-validated comprehensive mathematical models are invaluable.

High-quality comprehensive load and response measurements are also invaluable!
It has been a continual source of irritation to the wind industry to receive patronizing comments from the ‘conventionals’—oil, gas, coal and nuclear. Typically, these comments have a theme that states that the conventionals are grown up and know how to do complicated things, whereas the upstart wind energy business is so simple that it is difficult to tell what all the fuss is about. Although there is of course useful transfer of ideas and technology, this approach is not very helpful. It could be that this paper will be received by the MR industry in the same vein. That is not the intention! Each new renewable technology has its own challenges, and while there may be some common ground between them, they all have to plough their own furrow. Lessons from the engineering mistakes may be useful; those drawn from the political and commercial ones certainly will be. The future will be an eclectic mix of all the renewables and perhaps even a few conventionals if they can keep up. The raw potential for MR is vast and, if this paper has done a little to help exploit that potential a little faster than was possible for wind, then it has succeeded.

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