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The benefits of marine technologies within a diversified renewables mix

A report for the British Wind Energy Association by Redpoint Energy Limited

Version History

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1 Context

The operating characteristics of individual renewable electricity generating technologies powered by the forces of nature are becoming well understood. However, the impact of large penetrations of such technologies on electricity markets is the subject of much debate. Whether they are powered by wind, waves, the tides or sun, the fundamental difference between these technologies and more "conventional" thermal technologies is the inherent variability of their output and the fact that they are non-dispatchable[1]; when the required forces of nature are present, electricity generation can occur, and when they are not, it cannot. What complicates the matter further from an electricity market point of view is that there is often a close relationship between the output levels of the same technology in different locations. In a relatively small electricity system like Great Britain with low levels of interconnection, and where large parts of the country can be affected by the same weather system, this may lead to large variations in output, increasing the swing required from other, flexible plant in order to balance the system. However, by diversifying the mix of renewable technologies (i.e. adding technologies with weaker relationships between their output and wind levels) the variability in renewables power output can be reduced, resulting in reductions in the cost of meeting electricity demand.

The relatively low contribution of wind power to security of supply, and requirements for reserve capacity, have been well documented. Less well explored are the impacts that high output levels from significant penetrations of variable generation can have on electricity market prices and the profitability not just of those technologies but also of the remainder of the generation mix. The purpose of this study is to highlight some of the economic benefits of a more diversified mix of variable renewable electricity-generating (RES-E) technologies, rather than relying solely on wind power to provide the majority of renewable power for the GB market.

Marine technologies

Given its geography, there is massive potential for the UK to harness the power of waves and the tides around its coastline in order to generate electricity. In general, the majority of these "marine" technologies are currently only at the prototype stage, although recently there have been some commercial-scale installations. Three broad categories of marine technologies are covered in this analysis, and described briefly below[2,3]:

- **Wave**: There are currently many different types of wave-powered generator in the research stage, each with different operating characteristics. There is a positive correlation between wind and wave output[4], and output of wave-powered plant exhibits similar seasonality to that of wind plant. However, hour-to-hour changes of wave power output are less extreme than those of wind and the non-perfect correlation can provide a diversification benefit.

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[1] Their generation levels can be turned down but not up.

[2] More detailed information may be found on the website of the European Marine Energy Centre: http://www.emec.org.uk.

[3] It should be noted that the analysis did not assume any specific types of technology.

[4] Note that a positive correlation between wind and wave power output levels does not preclude the possibility of periods of low wave output and high wind output, and vice versa. The key point for the purposes of this study is that at the same offshore location, there will be a weaker relationship between the output levels of a wind turbine and a wave generation device than between the output levels of two wind turbines.

- **Tidal stream**: These technologies are similar in concept to wind turbines, and generate in areas where tidal currents are concentrated. Output levels vary based on the speed at which tidal currents pass through the turbines; there is no tidal flow (and hence zero output) at high and low tides, and the highest flow rates occur in between times on both incoming and outgoing tides. Tides follow an approximate 14-day Spring-Neap cycle, with considerable variance in output levels at different times within the cycle. Importantly, there is no correlation between tidal stream output and wind and wave output, and it is possible to forecast tidal stream output accurately in advance.

- **Tidal range**: Power has been generated successfully through large-scale tidal impoundment for decades. The process is conceptually similar to reservoir hydro generation; incoming tides fill a lagoon, and power is generated when the difference between the impounded lagoon of water and the outgoing tide (the "head") is large enough. If power is generated on the incoming tide as well, this is referred to as two-way generation, rather than ebb generation. As with tidal stream, there is no correlation with wind and wave output and it can be forecasted accurately.

The impact of the correlation between output levels of wind plant in different locations can be reduced somewhat by building wind plant in a diverse range of locations. Given the operating characteristics described above, variability in renewable power output levels can be reduced further by building technologies with lower correlations with wind power (e.g. wave technologies) or no correlation at all (e.g. tidal stream and tidal range technologies). This is the key benefit of technology diversity, and it is the impact of reducing this output variability that is explored in this report.

Impact on the GB electricity market

If the UK is to meet a 2050 target of reducing greenhouse gas emissions by 80%, the electricity sector will have to be substantially decarbonised. In the interests of long-term security of supply, generation will need to be provided by a combination of low-carbon technologies, including nuclear, renewables and technologies fitted with carbon capture and storage (CCS) technology. In this report, we start with a Base Case in which nuclear and wind power supply the majority of annual electricity demand (31% and 30% respectively), with the remainder provided by other renewable sources, such as biomass (9%) and conventional thermal generation (29%), mainly gas fired[5]. It is important to note that alongside Sizewell B, there is 19.2 GW of new nuclear capacity in the scenario, consisting of twelve 1.6 GW PWR plant. The UK Government has made a commitment to enable investment in new nuclear plant as a key means of decarbonising the electricity sector, and a pathway to an 80% reduction in electricity sector CO_2 emissions by 2050 could require a carbon intensity of approximately 125 kg/MWh[6] by the 2030s (see Committee on Climate Change, 2008). This is consistent with the annual emission rates in the Base Case. The capacity mix in the Base Case is broadly representative of a hypothetical year, sometime post-2030.

We then replace the quantity of wind generating capacity on the system in the Base Case in successive steps with sufficient capacity of wave and tidal power to maintain a *constant amount of combined generation* from wind and marine capacity[7]. In doing so, we quantify the benefits of diversifying the mix of renewable generation in terms of reducing the costs of meeting demand. These cost savings include reduced requirements for backup and reserve capacity, reduced redundant investment resulting from renewables 'spill', and reduced carbon dioxide emissions and fuel usage. We also quantify the potential impact on the level of subsidy required under the Renewables Obligation given the differences in the prices that variable renewables can capture with a more or less diversified mix.

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[5] For the assumptions used in this study combined cycle gas turbines were a more economic technology than coal fitted with CCS.

[6] The current carbon intensity of the power sector is approximately 500 kg/MWh.

[7] The straight replacement of wind capacity with marine capacity is somewhat simplistic, as it ignores the impact on investment in the remainder of the generating fleet that such replacement would precipitate. However, this impact is outside the scope of the study.

As noted above, marine technologies are still in the early stages of development and are currently around 10 years behind wind in the development timeline. As a result, the costs associated with these technologies are currently significantly greater than those of wind generation, although should be expected to fall rapidly through a 'learning curve' effect once large scale deployment begins. The areas of most potential for marine generation in the UK are remote, and hence the costs of connecting them to the transmission network may be greater than the equivalent wind capacity, particular onshore wind. Also, losses may on average be greater since at least some wind capacity will be located closer to the main centres of demand. We do not attempt to quantify the differences in capital costs, transmission costs and losses between different types and locations of renewables in this paper, as these have been analysed elsewhere. Instead, we focus our discussion on some of the cost savings in meeting demand and balancing the system that would result from diversifying the mix of renewable generation. These benefits should be considered when evaluating the 'optimal' mix of renewables capacity.

2 Modelling methodology and assumptions

The modelling has been undertaken for a hypothetical year in the future, with annual demand of 400 TWh[8] of which 39% is met by generation from renewables. Annual carbon dioxide emissions from the electricity sector for this year are approximately 51 million tonnes in the Base Case, representing a 75% reduction from 1990 levels.

Redpoint Energy's Volatility Model has been run multiple times to simulate hourly market outcomes for the year in question, starting from a Base Case in which wind plant have the potential to generate approximately 120 TWh of electricity. The quantity of wind capacity is then sequentially replaced with wave- and tidal-powered ("marine") generating technologies, maintaining total output from wind and marine at 120 TWh[9], effectively diversifying the mix of variable renewable generation.

The reduction in wind power and replacement with marine capacity was undertaken in two separate sets of runs: one in which total marine output was weighted towards wave power, and one in which contributions of wave and tidal output were equal. In both runs, output from tidal stream capacity was capped at 15 TWh[10,11]. In the first set, wave power made up the entire shortfall as wind was reduced. In the second set, tidal range capacity is included in the model so that output from tidal technologies as a whole remained equivalent with that of wave technologies[12]. The changing output levels are shown schematically in Figure 1 and Figure 2 below. Total generation from all variable renewable technologies is fixed at approximately 120 TWh (vertical axis), while the proportion of that 120 TWh provided by wind generation decreases (from left to right on the horizontal axis) and is replaced by marine power.

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[8] The hourly demand profile is assumed to be the same as that in 2008. Some of the results around the cost of spilled power would change if the demand profile changed over time.

[9] The volume-weighted capacity factor of the wind plant is approximately 32.4%.

[10] This assumption is based on the total GB potential estimated by Black and Veatch (2005). It should be noted that this potential is based on the exploitation only of localised, high speed tides. If new technologies are developed, which are able to exploit slower tidal speeds, then this total resource capacity could increase substantially.

[11] The variance in aggregate tidal stream output assumed in the modelling is consistent with that of a fully-developed system. The results presented in the following section for low levels of marine deployment (<30 TWh) would differ slightly with an assumption of lower variance for tidal stream output levels less than 15 TWh, however the likely impact across all the different metrics is not clear.

[12] We make no explicit assumption whether this tidal range capacity is from a single scheme, such as the Severn Barrage, or multiple smaller schemes; however, the output timing and profile we assume is consistent with the scheme(s) being located in the Severn Estuary. It should be noted that a single 8 GW Severn Barrage scheme could impose specific system balancing costs and impose additional costs on the transmission system. These are not considered in this analysis.

Figure 1 **Proportion of wind and marine technologies, excluding tidal range**

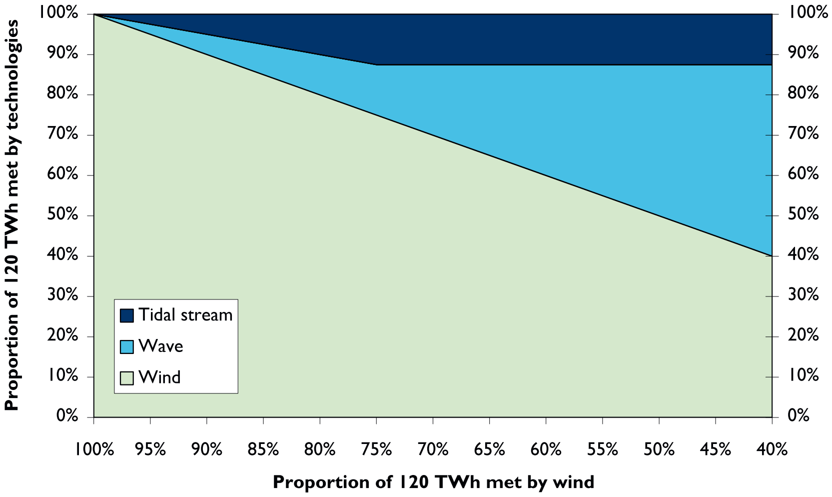
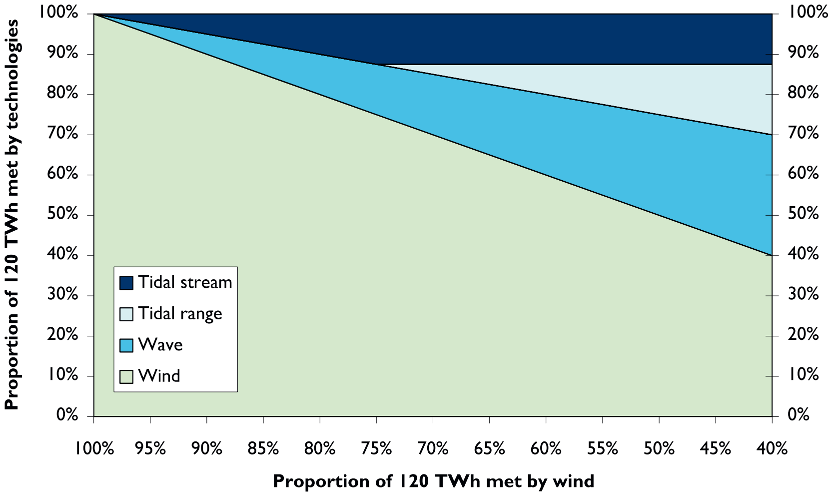


Figure 2 **Proportion of wind and marine technologies, including tidal range**



The remainder of the generating fleet comprises nuclear, combined cycle gas turbine (CCGT) and open cycle gas turbine (OCGT) capacity, small quantities of advanced super critical coal with CCS, and other renewable technologies such as biomass. The capacity of most of the remainder of the generating fleet is kept constant throughout the modelling runs, with the exception of CCGT capacity. As wind capacity is replaced with marine technologies, the quantity of CCGT capacity required to provide back-up can be reduced whilst maintaining exactly the same level of security of supply[13]. The exact quantities of CCGT capacity reduced are shown in Section 3.2 below.

[13] The metric used to measure security of supply is the expected energy unserved, which is the expected amount of demand per year that can not be supplied due to a shortfall in generating capacity. This is a rather more meaningful measure than the loss of load probability (LOLP), which only looks at the frequency, but not the size, of expected supply shortfalls. DECC (formerly BERR, 2007) provide a simple explanation of this concept, along with a case example.

The total expected energy unserved in each modelling run is approximately 1.5 GWh – slightly lower than today's level of security of supply, and consistent with a 7.5% de-rated peak capacity margin (the margin in 2008 was approximately 10%). Further information on these metrics may be found in Redpoint's supporting document to the Renewables Consultation (2008) – see link provided at the conclusion of this document.

The Volatility Model

Redpoint Energy's Volatility Model is an hourly market dispatch model, run within a Monte Carlo simulation framework. The model simulates hourly demand, spot fuel prices, forced outages and hourly renewables output. It produces annual price duration curves, estimates of price volatility, distributions of supply shortfalls and volumes of expected energy unserved, among other metrics.

Within the model, new wind, wave and tidal capacity is allocated to regions of GB based on expected deployment rates. At each iteration of the model, wave plant are assigned randomly to one of five regions (two in the north-west, two in the north-east and one in the south-west); wind plant are assigned to one of seven regions for onshore and eleven regions for offshore. Generation output levels in each hour across different regions are correlated accordingly[14].

Assumptions

A range of assumptions have been made in order to complete this analysis, many of which will have a material impact on the analysis. These assumptions include:

- The locations of the wind, wave and tidal stream capacity
- The operating characteristics and performance of different renewable technologies
- The composition of the remainder of the generation capacity
- The amount of capacity built to transmit power generated by those technologies
- Fuel and carbon prices

Further key assumptions are shown in the Appendix. All prices and costs are in real 2009 terms.

It should therefore be noted that the results could change significantly under a different assumption set, and therefore should be treated with caution. However, we would expect that directionally the results would remain unchanged.

3 Benefits quantification

3.1 The impact of diversification on output variability

The key impact of diversifying the mix of variable renewable technologies is in reducing the variability of the hourly aggregate output levels. Generation levels from wind farms have well-documented properties, including the possibility of sustained periods with low or no output. Diversifying the locations of wind farms can mitigate this risk to a certain extent. However, introducing marine technology significantly reduces the risk of long periods of low renewables output.

This point is illustrated clearly in the 2006 Carbon Trust report on diversified renewable energy resources prepared by Graham Sinden. In the study he notes that diversification decreases variability in the aggregate output from renewable generators, with the consequence that the contribution of the

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[14] Correlations between wind output levels from different regions of the UK have been calculated using the function presented by Sinden (2007). Further information on the Volatility Model may be found in Redpoint's supporting document to the Renewables Consultation (2008), although the model has been significantly enhanced since that publication. In particular, the locations of deployment of tidal and wave capacity, and the modelling of the output of both types of technology (including correlations between wind and wave regions), have been further calibrated against the work of Sinden (2005).

It should be noted that the characteristics of wind power output are well understood, and are backed up with a considerable quantity of observed data, from which the parameters in the Volatility Model have been estimated. However, observed output from marine plant is not as readily available, and therefore insights rely to a greater extent on modelled outcomes.

overall renewable portfolio to security of supply increases substantially. The distribution of total output per hour becomes narrower when marine technologies are included, reducing the probabilities of both low output levels (<5% of maximum capacity) and high output levels (>70%) compared to a distribution of wind output alone. The resulting benefit to security of supply discussed by Sinden is also shown by this study, as presented in Section 3.2 below.

Interestingly, the variability of hourly changes in aggregate output levels may increase when the mix of renewable capacity becomes more diversified. This is in part due to the fact that total output from tidal stream plant changes to some extent every single hour, whereas output from wind (and wave) at least has the possibility of remaining constant, particularly if aggregate output levels are near or close to zero. However, despite the increase in average hourly variability, the most extreme hourly changes will occur in a wind-only system.

The conceptual results around output variability presented by Sinden are reflected in our own analysis, and hence are not described further in this document. It is important to note that the reduction in volatility of the aggregate output of the variable renewable technologies is the key benefit of diversification. The impact of this reduction manifests itself in several different areas, which we describe below.

3.2 Reduced requirement for back-up capacity

Capacity credit

One measure used to determine the contribution to system reliability of variable renewable generation, such as wind power, is the capacity credit. A plant's *capacity factor* measures its average output over a given time period relative to its installed capacity, whereas the *capacity credit* traditionally measures the percentage of maximum potential output that statistically can be shown to contribute to security of supply. The capacity credit is often expressed as the amount of conventional thermal generation (taking into account its expected availability) that variable generation could effectively "replace" without any reduction in security of supply. It is therefore meant to be a like-for-like comparison of the contribution to security of supply different types of generation, with different output patterns and availability[15].

As discussed by Gross and Heptonstall (2008), the favoured approach for estimating capacity credit functions is via statistical analysis using simulation models. The capacity credit functions used in our analysis have been calculated using stochastic techniques within the Redpoint Volatility Model, and have then been benchmarked against other studies[16] to ensure consistency.

The capacity credit for total installed variable capacity in Great Britain will generally be lower than the sum of individual plant capacity factors, and is also a function of the mix of plant on the system and the level of interconnection. In particular, the average capacity credit for a given technology will be affected by:

- the total existing installed capacity of that technology on the system; and,
- the geographical distribution of different variable technologies and relationships between output levels at different locations.

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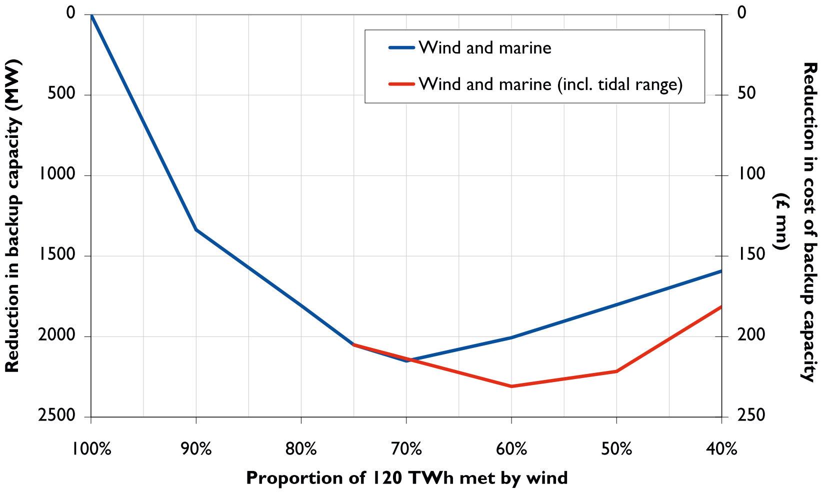
[15] Supply shortfalls have the potential to occur at times well away from peak load, and may be caused by shortfalls in thermal capacity due to unplanned outages. Given that we simulate the availability of each unit on the system throughout the year, our capacity credit measures the contribution variable renewable capacity makes to security of supply across an entire year, not just at the single hour of peak demand, which Skea et al (2008) note is the correct approach, "in principle".

[16] The main source of published capacity credit data points used was published by the UK Energy Research Centre (Gross et al.) in 2006.

The first of these factors results from the fact that the output levels of individual units of variable capacity of any single technology (such as wind) are generally correlated. As a result, while the first unit of a technology deployed may have a capacity credit close to its capacity factor, the average capacity credit declines as the installed capacity of that technology increases. Each extra unit of installed capacity yields a diminishing margoutput hours) will be correlated with those of the remainder of the installed capacity. For the example of wind, the first MW on the system may have a marginal capacity credit of close to 30%, whereas the 40,000th MW may have a marginal capacity credit below 5%. Thus the difference between each additional unit's capacity factor (constant) and its capacity credit (diminishing) increases with penetration. For the purposes of this study, we define the requirement for capacity to 'back-up' variable renewables to be the difference between the aggregate capacity factor and the aggregate capacity credit[17]. Therefore, the amount of back-up capacity required increases as more variable renewables capacity is built.

It could therefore be expected that replacing the last *n* MW of wind capacity, itself contributing relatively little incremental benefit to security of supply, with wave and tidal capacity, the output of which has low (in the case of wave) or zero (in the case of tidal) correlation with wind output, should lead to an increase in the total capacity credit of the combined renewables mix, and hence lead to a reduction in the amount of back-up capacity required. However, as more wind capacity is replaced, the incremental capacity credit of the replaced capacity increases, and the incremental credit of the wave and tidal capacity with which it is being replaced decreases. This suggests that there is an optimal mix of variable technologies in terms of the amount of back-up capacity required. This is shown in Figure 3 below.

Figure 3 Reduction in back-up capacity required and back-up costs[18]



For the replacement of the first 10% of wind capacity (around 4.34 GW), the need for around 1.35 GW of back-up capacity is removed. At this point, the difference between the capacity credit of the wind plant being replaced and the wave and tidal plant introduced is around 28%, despite similar average capacity factors for each technology. There is a disproportionately large benefit for the introduction of the first few GW of marine technology, as this is when the incremental benefit of the marine technology in terms of security of supply is greatest.

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[17] Some argue that variable renewables cannot be relied upon to provide any output at times of peak demand, and hence suggest that back-up capacity is required up to the aggregate capacity factor of renewables,

[18] Savings in back-up costs are calculated as the avoided annual cost of back-up capacity, i.e. annualised capital costs plus annual fixed costs, which is approximately £100/kW. The savings in variable costs due to reduced running from this backup capacity have not been estimated; however, the load factor of this extra capacity would be very low.

The maximum reduction in back-up capacity is around 2.15 GW for a mix including 30% marine and 70% wind, before increased levels of wave generation require greater levels of back-up. However, if some tidal range is included within the marine capacity, the reduction in the total amount of back-up required increases further to 2.3 GW, with a minimum at 60% wind. This equates to a not insignificant 5% increase in the average capacity credit of the combined renewable capacity.

The maximum saving in the annual costs of back-up capacity (excluding fuel costs) is approximately £230m. Note that the savings could be significantly lower if the reduced requirement for thermal capacity were manifested in earlier closures of older plant, rather than reduced build of new plant.

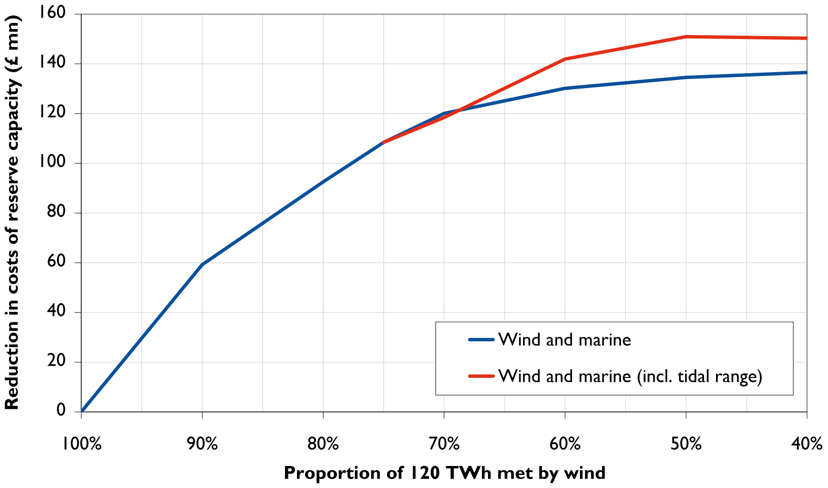
3.3 Reduced volume and cost of reserve and balancing capacity

The accuracy with which changes in wind power output can be forecasted several hours out is a growing area of research, and impacts significantly on the amount of reserve capacity that must be provided. Reserve capacity is required to fill sudden and unforeseen shortfalls in supply or increases in demand; and hence improving the ability of the system operator to predict such changes will reduce the requirement for such capacity.

Output from wave power plant is much less variable than that of wind plant, and can be forecasted with more accuracy, while output from tidal plant may be predicted accurately years in advance. The increased predictability of a diversified renewables mix, combined with a reduction in maximum hourly changes in output, should reduce the requirement for reserve[19].

Much of the reserve requirement will be provided by part-loaded thermal plant able to ramp up and down at short notice to cover short-notice fluctuations in variable plant output. Whilst the plant is part-loaded, it is likely to be operating at a loss (otherwise it would prefer to operate at full output). Hence, we have estimated the costs of reserve by calculating the difference between the price captured and the short run marginal cost of the plant for the volume of reserve required in each case. The total cost of reserve reduces as diversity increases. The cost savings are shown below in Figure 4.

Figure 4 Reduction in costs of part-loaded reserve capacity



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[19] It should be noted that the function for reserve capacity used in this analysis is based on a function provided by National Grid, taking into account likely maximum changes in output levels from renewable generation. However, the function does not take into account the risk of outage of a large single tidal range installation such as the Severn Barrage. Such a large scheme in a single location may also pose additional system balancing costs which are not accounted for in this analysis.

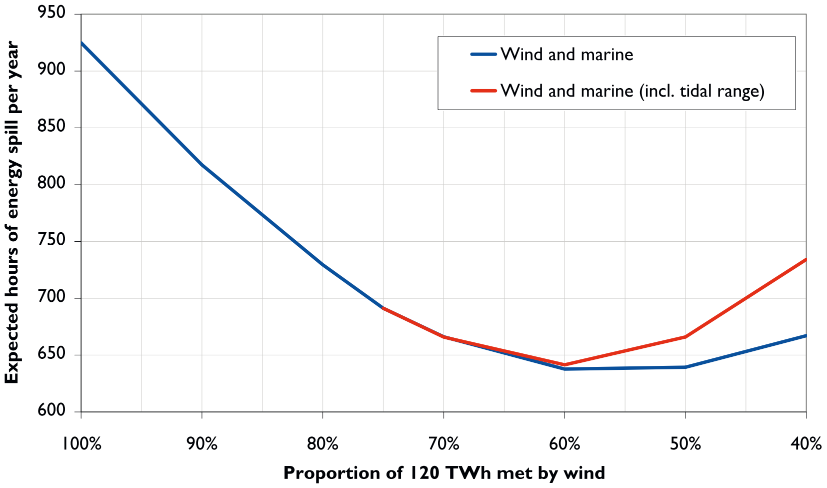
3.4 Reduced frequency and quantity of spilled power

As well as reducing the requirement for back-up capacity, the lower variability of total output from a diversified mix of variable renewables also reduces the risk of periods occurring in which total output from non-dispatchable sources exceeds total demand. In the future, the competition between must-run plant to meet low levels of demand, identified by Gross and Heptonstall (2008), will lead to some power effectively having to be "spilled". While nuclear plant may be able to reduce output to accommodate output from renewable plant, unless the flexibility of new nuclear plant increases significantly the extent to which this is possible is limited.

With wind providing all 120 TWh of variable renewables output, power would be spilled in around 10.6% of all hours of the year[20] given the assumptions used in this analysis[21]. The total volume of spilled electricity would be around 6 TWh annually. The volume of spill could be reduced by greater interconnection, more dynamic demand response, for example charging of electric cars, or by diversifying the mix of renewables.

Figure 5 shows the effect of the latter. For a wind:marine mix of 60%:40% the volume of spill would be approximately halved to 3 TWh per year. Interestingly, the introduction of tidal range capacity would have less of a benefit to spill than a mix with the same amount of wind but no tidal range. It has a lower capacity factor than wave power, so requires more MW of capacity for each MWh of output, and the operating characteristics of tidal range mean that it has a higher probability of operating at or near its maximum capacity, relative to wave power. These two factors combined result in higher probabilities of spilled energy occurring[22].

Figure 5 Occurrence of spill



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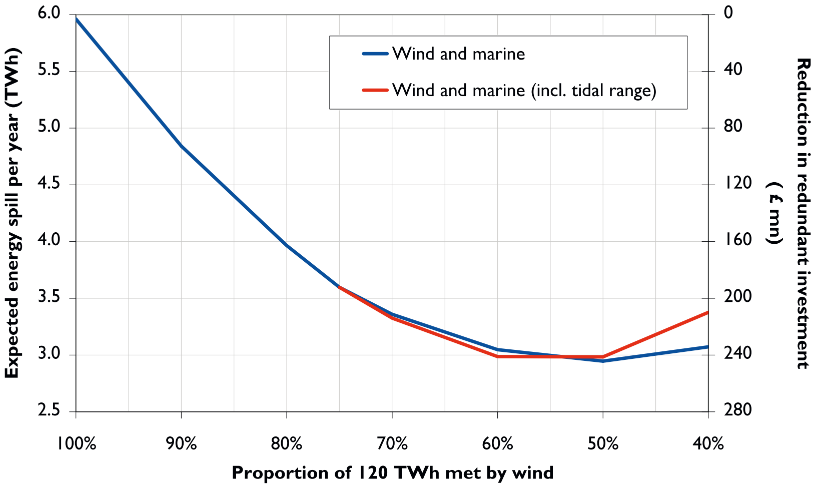
[20] Off-peak demand troughs at 25.3 GW under these conditions. Given nuclear capacity of over 20 GW, and over 40 GW of non-dispatchable renewable capacity, renewable output does not have to be particularly close to average conditions to present a real risk of spill, despite the much lower average output of wind plant in low demand periods shown by Sinden (2007).

[21] For the purposes of this study, existing nuclear plant (as of 2008) are assumed to be 100% inflexible (i.e. they must operate at maximum capacity when they are available), whereas new nuclear plant (commissioned post 2008) must operate at a minimum of 90% of total capacity. The remaining 10% can be ramped up and down to follow (residual) demand, and hence may set the price at their short-run marginal cost of generation. In periods when residual demand is low or negative, we do not assume any increase in demand due load-shifting, however we do include pumping by pumped storage and exporting through interconnection to continental Europe. Alongside existing interconnection capacity, we assume that there is also a 1.3 GW BritNed interconnector. Therefore the maximum export quantity in periods of low residual demand is 3.3 GW, assuming that power cannot be exported to the Irish market due to the correlation in wind patterns.

[22] Note also that conversely, if marine technologies had higher capacity factors than those assumed in this report, the reduction in spill would be greater, due to the lower total MW capacity generating the same TWh output.

It may be assumed that the 120 TWh of wind generation is part of some overall renewable energy target. If this is the case, around 6 TWh of the 120 TWh is being spilled, and only 114 TWh of wind output would count towards the target. The capacity producing this output is effectively 'redundant' investment[23]. The reduction in spill of around 3 TWh achieved by diversifying the renewables mix would reduce redundant investment by around 1180 MW[24]. Based on the current costs of onshore wind, the annual saving would be approximately £240 mn per annum. This is shown in Figure 6 below.

Figure 6 Total amount of spilled energy per year, and reduction in 'redundant' investment



3.5 Reduction in carbon dioxide emissions and fuel usage

As shown in Figure 7 below, carbon dioxide emissions are reduced through diversity. This is for the following reasons:

- Less zero-carbon renewable generation is spilled, requiring less generation from the conventional fleet to meet annual demand
- Reduced part-loading of conventional plant for reserve and system balancing
- Reduced volatility of the combined output of renewable plant, requiring less generation from the more expensive and lower efficiency (hence high carbon) conventional generation

To put these figures in context, the total annual emissions for the Base Case are approximately 51 million tonnes. Therefore increasing diversity can reduce emissions by up to around 6% compared to the Base Case.

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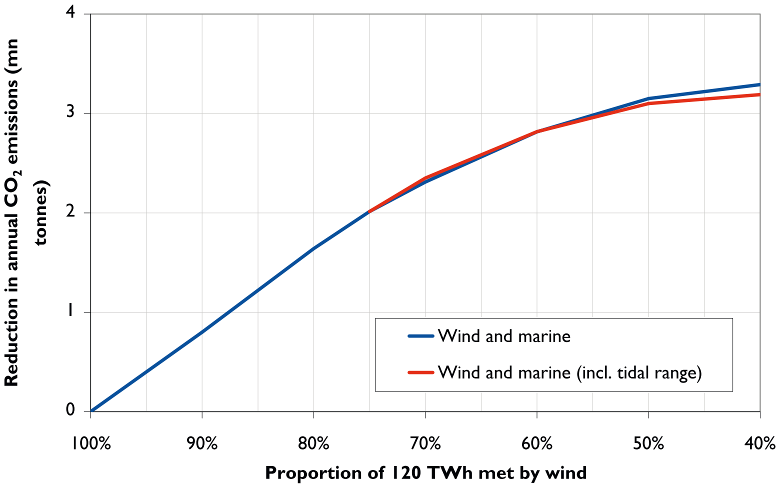
[23] It is obviously not the same specific capacity producing all the 6 TWh of spilled energy; however, this simplifying assumption is made in order to calculate the cost of the spilled energy in terms of redundant investment.

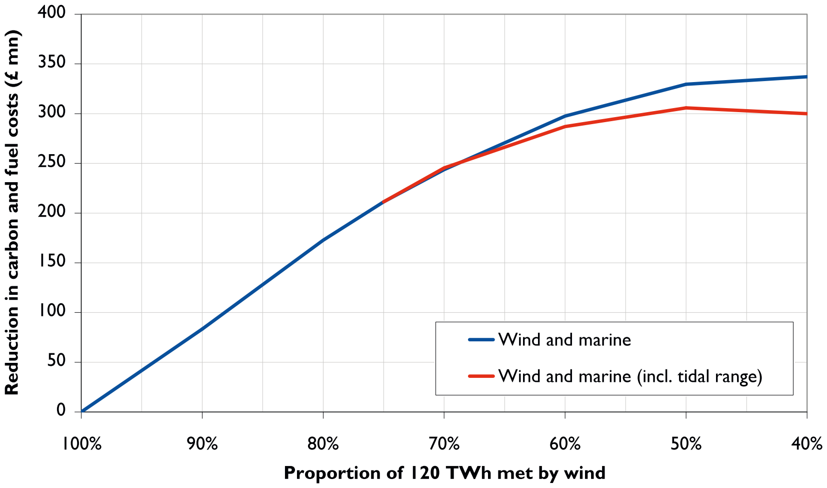
[24] This assumes a capacity factor for a new onshore wind farm of 29%.

Figure 7 **Reduction in total annual power sector CO_2 emissions**[25]



For the same reasons that carbon dioxide emissions may be lower with a more diversified renewables mix, fuel usage should also be reduced. Figure 8 below shows the combined savings in fuel and carbon dioxide costs with a more diversified renewables mix.

Figure 8 **Reduction in costs of fuel usage and CO_2 emissions**



3.6 Levels of subsidy required under the Renewables Obligation

The purpose of the Renewables Obligation is to provide renewables with an additional revenue stream to make them competitive with conventional generation. If electricity prices fall then the level of subsidy required for renewables investment to proceed may need to go up, but if electricity prices rise the level of subsidy required could fall. The ability to 'band-up' or 'band-down' certain technologies

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[25] Note that this is the reduction in annual CO_2 emissions for a *fixed* amount of renewable output. Increasing the penetration level of renewables above 40% would decrease CO_2 further. CO_2 is valued at 30 €/t, as per the assumptions in the Appendix,

within the Renewables Obligation provides the Government with a mechanism to adjust subsidy levels should this be required in the future.

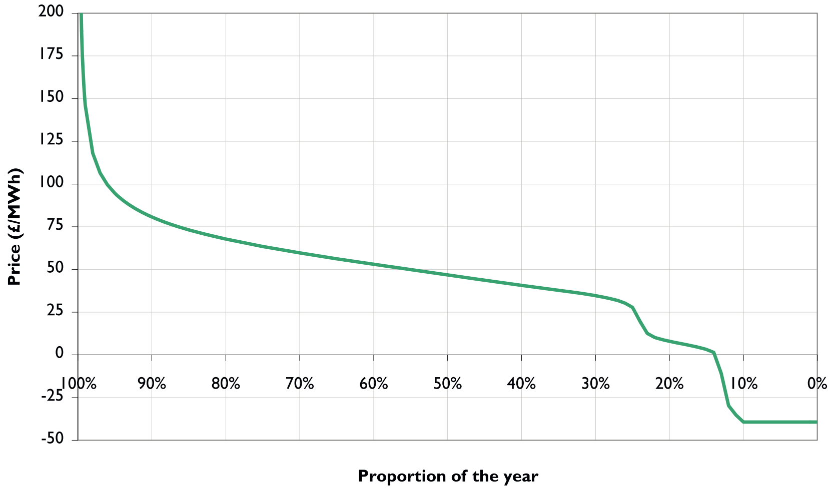
Given their non-dispatchable nature, variable renewable generators such as wind plant are "price-takers", operating when the forces of nature allow. The greater the wind blows, the more revenue the wind plant should earn. However, as the proportion of wind on the system increases the price that wind plant can capture diminishes (*ceteris paribus*), since prices will tend to fall the windier it is. As a result the level of subsidy required to support future investment may need to increase to offset the effects of diminishing wholesale revenues.

For current penetration levels, wind plant in GB should, in theory, be able to capture a price slightly better than the baseload price (notwithstanding typical discounts in offtake agreements of around 10-15% to take account of volume and balancing risk), given that wind speeds are, on average, stronger during the day than at night, and stronger in winter than in summer, coinciding with periods of higher energy prices. However, as penetration levels rise, the impact that wind plant have on power prices starts to become more apparent, as has shown to be the case in countries such as Spain, Germany and Denmark. Significant volumes of wind generation in a given period will displace thermal generation and reduce the cost of the marginal plant, thereby reducing market prices. There begins to be a negative correlation between wind output and the price that they receive; the higher the wind capacity, and the more correlated the output levels of those plant are, the lower the prices that capacity will receive for each MWh of power generated. Conversely, prices will be higher when wind generation levels are low.

Periods of energy spill further depress the price that variable renewables can capture, and the subsidy is effectively leaked. Under the current market arrangements, renewable generators only receive Renewables Obligation Certificates (ROCs) when they generate, and will therefore price in the opportunity cost of lost ROCs in bidding to turn down generation. In hours when energy is being spilled, a wholesale electricity price of minus ROC price (around -£39/MWh in this scenario) is assumed[26].

Figure 9 below illustrates the effect of spilled electricity on the annual price duration curve, for the case with 100% wind output. The far right-hand step, with prices at -£39/MWh, occurs when electricity is spilled. The step above that is set by flexible nuclear plant on the margin in periods of low (but positive) residual demand, potentially increasing their output up to maximum capacity in order to export to continental Europe. The remainder of prices are set by other thermal plant.

Figure 9 Annual price duration curve, 100% wind (Base Case)



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[26] Although this price is significantly below the short run marginal costs of operating nuclear plant, we assume that these plant would not be shut down for short periods in order to avoid large start-up costs.

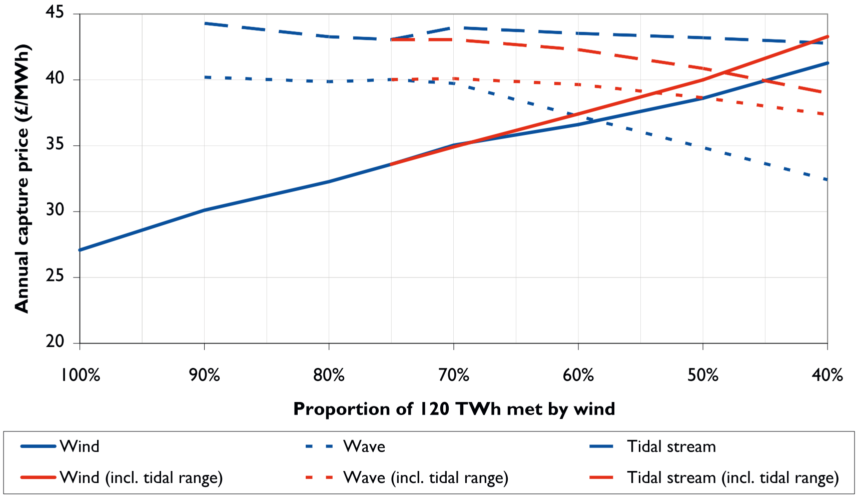
However, by diversifying the renewables mix, all variable renewables plant should benefit since with a less variable profile of renewables output there should be fewer periods with low or negative prices. This should increase the wholesale revenues that each plant can earn and in turn reduce the levels of subsidy required for renewable generators.

Figure 10 below shows volume-weighted (capture) prices received by wind and marine plant under different renewables mixes. Here, for simplicity we are assuming that renewables are selling their output in the spot markets. In reality only a small percentage of power is traded this way, and most renewables plant will have signed long term offtake agreements or be part of the integrated generation portfolio of a utility. Nonetheless, in a well functioning market it can be assumed that changes in spot prices will be reflected in forward and contract prices and hence the simplifying assumption is a valid one.

With 100% wind, wind generators capture an average price of only £27/MWh, compared to baseload prices around £43/MWh, a discount of 37.4%[27].

As wind capacity is replaced by marine capacity, wind's capture price increases substantially. Conversely, the capture prices of marine capacity generally decrease as their penetration increases, due to the increased price-dampening effect that the greater penetrations have on periods when they are generating most. Wind and wave plant benefit from the introduction of tidal range instead of extra wave capacity (represented by the red lines in Figure 10), whereas tidal stream plant do not. This is due to the positive correlation between wind and wave plant output, and the lack of correlation between their output and the output of tidal range plant. Due to the impact of the Spring-Neap tidal cycle on tidal-powered generation, the output patterns of the two types of tidal-powered plant are positively correlated, albeit with different timings.

Figure 10 Change in volume-weighted capture prices received by variable generators



Given the changes in capture prices for each technology through diversification, and in particular the change in the capture price of wind, the total energy market revenue received by the 120 TWh of variable renewables generation increases substantially as the proportion of wind power decreases. The increase in total revenue is shown below in Figure 11. This additional revenue in theory reduces the amount of subsidy required to meet a certain level of renewables generation. For example, a £1.4 bn increase in revenues from the wholesale market for a 60%:40% wind:marine mix could reduce the

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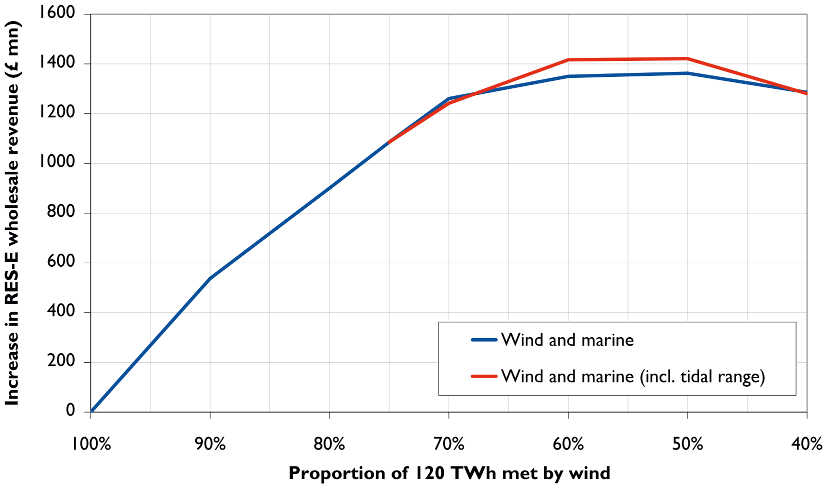
[27] While not shown in this report, each different wind "region" in the model has a different capture price. Those regions in parts of the country containing large quantities of wind capacity have significantly lower capture prices than regions in areas of lower development.

required size of the Renewables Obligation by around 16%, notwithstanding differences in capital costs between technologies which may require different banding.

Figure 11 Change in total annual revenue earned by wind, wave and tidal generation



The extent to which consumers could benefit from lower Renewables Obligation costs under a more diversified renewables mix will depend on the impact on wholesale electricity prices. In general, we might expect wholesale prices to be higher with a more diversified mix since there will be less occurrence of periods with very low or negative prices. Hence, the overall benefit to consumers might be significantly lower than £1.4 bn.

3.7 Overall benefits

We have described above a number of potential benefits from a more diversified renewables mix. Table 1 and Table 2 below show the cost savings, for three different wind:marine mixes, with and without tidal range respectively. This shows that there is a substantial benefit to diversification. To put these savings in context, the total annual value of the wholesale electricity market in the Base Case is around £28 bn[28]. Therefore these savings are up to 3.3% of the annual wholesale cost of electricity. There may be additional savings resulting from better utilisation of the transmission system, since the peaks in variable renewables output may be lower requiring less transmission capacity, or reducing the costs of managing transmission congestion. However, quantification of these effects was outside the scope of this study.

The 60%:40% wind:marine mix appears more beneficial than the 40%:60% mix. This reflects the fact that there is likely to be greater inherent diversification within the wind portfolio given a wide geographic distribution of wind plant, whereas marine technologies are more likely to be concentrated in fewer locations.

[28] The total cost of wholesale electricity is £19 bn, and the total cost of the Renewables Obligation is £9 bn.

Table 1 **Total cost savings per year from diversifying the mix of renewables, excluding tidal range**

Wind : Marine	100% : 0%	75% : 25%	60% : 40%	40% : 60%
Reduced back-up capacity (£ mn)	0	205	201	159
Reduced costs of reserve capacity (£ mn)	0	108	130	137
Reduced costs of fuel and CO_2 emissions	0	211	298	337
Reduction in extra renewable capacity required to replace spill (£ mn)	0	192	236	234
Total savings (£ mn)	**0**	**717**	**865**	**867**

Table 2 **Total cost savings per year from diversifying the mix of renewables, including tidal range**

Wind : Marine	100% : 0%	75% : 25%	60% : 40%	40% : 60%
Reduced back-up capacity (£ mn)	0	205	231	181
Reduced costs of reserve capacity (£ mn)	0	108	142	150
Reduced costs of fuel and CO_2 emissions	0	211	287	300
Reduction in extra renewable capacity required to replace spill (£ mn)	0	192	241	210
Total savings (£ mn)	**0**	**717**	**901**	**841**

Assuming the market is competitive, these cost savings should be passed through to consumers. There is the additional potential benefit to consumers in terms of reduced costs of the Renewables Obligation. However, this may be offset to a greater or lesser extent by increased wholesale electricity prices, and since both the ROC price and wholesale electricity price represent transfers between producers and consumers, rather than real resource costs, these are not included in the tables above.

It should be noted that some of the benefits of diversification could also be achieved through greater interconnection and a more dynamic demand side, which could be enabled by smart grids, smart metering and other new technologies, such as electric cars. The quantification of these potential benefits was outside the scope of this study.

4 Conclusions

This paper has described five potential benefits of a more diversified renewables mix, namely a reduced requirement for backup capacity, and similarly reserve capacity, less 'redundant' investment in renewables, lower carbon dioxide emissions and fuel usage, and a possible reduction in the size of the Renewables Obligation.

The analysis suggests that annual cost savings from a diversified renewables mix could be very significant, as much as 3.3% of the annual wholesale cost of electricity, for the assumptions used in this paper. This suggests that marine technologies can complement wind, increasing the cost effectiveness of variable renewables, and ultimately expanding the potential share for renewables in the overall generation mix.

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6 Appendix – Assumptions

Table 3 Key numerical assumptions[29]

Item	Assumption(s)
Annual demand (TWh)	400
Peak demand (GW)	70.9
Tidal stream capacity factor[30]	35%
Tidal range capacity factor[31]	23%
Wave capacity factor[32]	30%
Onshore wind capacity - Base Case (GW)	25.7
Onshore wind capacity factors (varying by region)	29%, 27%, 21%
Onshore wind capital cost (£/kW)[33]	1370
Onshore wind annual fixed cost (£/kW)	45
Offshore wind capacity - Base Case (GW)	17.7
Offshore wind capacity factors (varying by region)	41%, 35%
CCGT forced outage rate	10%
CCGT maintenance rate	7%
CCGT capital cost (£/kW)	665
CCGT annual fixed cost (£/kW)	22
Economic lifetimes for wind and CCGT (years)	20
Discount rate for wind and CCGT	10%
Annual availability for nuclear plant	87%
Gas price (p/thm)	60
Coal price ($/t)	96
Gasoil price ($/t)	736
LSFO price ($/t)	410
CO_2 price (€/t)	30
Renewable Obligation Certificate price (£)	39.34
Exchange rate (€:£)	1.2:1
Exchange rate ($:£)	1.6:1

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[29] Prices and costs are real (2009).

[30] Ernst & Young (2007).

[31] Severn Tidal Power Group (2006).

[32] Ernst & Young (2007).

[33] Capital costs, maintenance rates and forced outage rates are based on anecdotal and historic evidence.